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Modeling Stormwater Pollutant Transport in a Karst Region--Bowling Green, Kentucky

Allison H. Ross
Western Kentucky University, allison.ross193@wku.edu

MODELING STORMWATER POLLUTANT TRANSPORT IN A KARST REGION – BOWLING GREEN, KENTUCKY

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MODELING STORMWATER POLLUTANT TRANSPORT IN A KARST REGION – BOWLING GREEN, KENTUCKY

Date Recommended __7/27/09____________

__Jun Yan____________________________
Director of Thesis

__Chris Groves_________________________

__David Keeling_______________________

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Dean, Graduate Studies and Research Date

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Allison H. Ross August 2009 99 Pages

Directed by: Drs. Jun Yan, John All, Chris Groves, Lee Florea

Department of Geography & Geology Western Kentucky University

The management of stormwater runoff is a particular challenge for communities in karst regions. Most guidelines for compliance with regulations for stormwater monitoring and mapping pertain to non-karst environments. It can be argued that effective stormwater management is even more essential to karst regions because stormwater receives little or no natural filtration as it is transferred through conduits in the subsurface and the buildup of pollutants underneath can be detrimental to community and environmental health if not effectively mitigated. Because of the limited resources available to determine how stormwater runoff carries potential pollutants across the surface before being transferred to the karst subsurface and then reentering back on the surface across the landscape, this study aims to use geographic information systems (GIS) to investigate this problem. The objectives of this study are twofold. The first objective is to understand the transport mechanisms for stormwater runoff and how the movement through karst systems differs from non-karst systems, especially in regards to the surface and subsurface interactions. The second objective is to develop a general procedure for predicting stormwater runoff pathways in karst regions using GIS technologies and spatial analysis techniques – including identifying which data and

techniques are essential to analyze surface and subsurface processes - to improve stormwater monitoring effectiveness.

The premise of this study is broken down into a conceptual model with three significant components: Surface Input (stormwater runoff on surface), Subsurface Transport (stormwater transport through subsurface), and Output to Surface (output of stormwater to the surface via springs). The first component utilizes Hydrological Analysis and Network Analysis techniques to determine stormwater runoff pathways from potential point-source pollutant sites across surface to injection points where runoff enters subsurface. The second component uses Spatial Interpolation Techniques and Hydrological Analysis to predict subsurface accumulation areas that collect runoff from injection points and subsurface conduit pathways to output locations. The third and final component examines the output of the runoff back to the surface and identifies the locations where stormwater runoff can be sampled.

The analyses of the Surface Input component proved to be effective in predicting the behavior of stormwater runoff between pollutant sites and their corresponding injection points. The analyses of the Subsurface Transport captured the overall patterns in the inferred dye tracing pathways that were used as the control dataset. The Output to Surface established the linkages among RCRA sites, their corresponding injection points and ultimately their output springs. These findings are very useful in developing informed stormwater sampling strategies and plans. In future investigations, these results could be verified with stormwater sampling and additional dye tracings and can be improved in two ways: more complete datasets of all stormwater features in the area – especially springs and drywells, and a more extensive and equally distributed dataset for groundwater depths across the study area to create a more accurate interpolated potentiometric surface.

CHAPTER 1 INTRODUCTION

Managing stormwater runoff often presents a big challenge for many communities. Rain water usually accumulates pollutants from surfaces, such as parking lots or roadways, and point sources, such as commercial and construction sites, before entering surface streams or groundwater systems without any treatment or removal of contaminants. The management of stormwater runoff especially concerns communities in karst regions because of some unique characteristics associated with karst environment, such as limited filtration by soil buffers, well water contamination, combustible buildup in karst passageways, etc. In karst regions, stormwater runoff can quickly enter the karst system through drywells and other injection points; even stormwater that settles in a retention basin does not receive much filtration through the shallow soils before entering the karst groundwater system through fissures in the limestone filtration. The City of Bowling Green, Kentucky, located in South Central Kentucky, is one of these communities affected by the added complications of stormwater runoff management due to its karst geology. Because of this, the city has been twice identified as an U.S. Environmental Protection Agency (EPA) Superfund Emergency site – once in 1983 and again in 1985 (Crawford, 1989). In some cases, pollutant runoff into the karst system creates a toxic buildup of combustible fumes that seeped into homes. Fortunately there were no explosions as a consequence of the buildup in the study area. However, similar environmental characteristics at a site in Pennsylvania lead to an explosion, creating a crater 25 feet in diameter (Crawford, 1989). Aside from the environmental safety issues that can arise from pollutant runoff into the karst groundwater system, human drinking water is subjected to potential contaminant by stormwater runoff. The Karst Waters Institute (KWI) states that 20% of the United States aquifers are located in karst regions, and 40% of groundwater used for drinking comes from karst aquifers. These issues were identified in the Karst Landscape Analysis Technical Report for Warren County (Crawford, 1989). The report also encouraged best management practices to be incorporated in order to protect groundwater resources.

Realizing the significance of the pollutants that stormwater runoff can carry into groundwater systems, the EPA has enacted numerous policies requiring the compliance on a variety of standards for monitoring, permitting, Best Management Practice (BMPs) implementations, inspections, and education relating to minimizing the impacts of pollutants accumulated in stormwater runoff. Part of the Clean Water Act (CWA) Phase II Stormwater regulations (1999) includes the creation of a map of stormwater structures as well as the development of a stormwater monitoring plan. In addition, discharge permits for pollutant release is covered by the EPA's National Pollutant Discharge Elimination System (NPDES), under which there is a subsection dedicated entirely to stormwater permitting and management. Stormwater runoff permits must be issued for large construction sites, municipal stormwater systems, and industries. Stormwater runoff monitoring is required to be in compliance with the permits, and sampling must be done by state and local agencies to ensure permits being followed. Another EPA Act instated for human health is the Safe Drinking Water Act (SDWA). One of the stipulations of this Act is an assessment of all drinking water sources – both surface water and groundwater - to determine potential contamination of the source and how susceptible the drinking water is to contamination. These are just some of the compliance guidelines set forth by the CWA and the SDWA to help ensure that stormwater runoff does not negatively impact human health and natural environment.

However, a potential problem with these regulations is that there are very limited provisions made specifically for those communities in karst regions. For instance, guidelines provided by these regulations for the implementation of sampling strategies and monitoring plans deal primarily with water accessible from surface that can be easily mapped and the hydrological properties can be easily obtained relatively about the area being sampled. But in karst regions it is usually much more difficult and expensive to create hydrological maps because once the water enters subsurface conduits, the paths that it takes through the ground are often unclear, making water quality sampling and monitoring capabilities limited at best. The study area of this research, the City of Bowling Green, KY, is fortunate to have many academic resources – from Western Kentucky University (WKU) – available for research, cave mapping & surveying, and dye tracing karst water features, but these capabilities are often expensive and time consuming for many other communities needing information about the underground conduit systems in order to make educated plans for stormwater monitoring and control. This calls for the development of a system that can be used to supplement dye tracing data to predict stormwater runoff pathways, on both surface and subsurface, and aid in the identification of viable sampling locations while minimizing the extensive cost of the conventional techniques, such as dye-tracing, cave mapping & surveying, etc.

The advance of geographic information systems (GIS) provides many communities with a collection of tools to collect and edit spatial data as well as document attributes and perform spatial analysis functions to make better decisions regarding many geographically-related problems. In many stormwater management practices, GIS technologies are commonly used in conjunction with municipal water resource management in non-karst regions, however very limited cases have been documented about the use of GIS and water management in karst regions in the existing literature. An increase in the applications of GIS-based techniques pertaining to stormwater management in karst regions would enhance the knowledge base for water management municipalities and karst hydrologists alike, as well as establish functional protocols for the application of GIS as a cost effective means to aid in the understanding surface and subsurface hydrological process in karst regions. In summary, there are two primary objectives of this study:

1) **Objective I** is to understand spatial process of stormwater pollutant transport in a typical karst region, Bowling Green, Kentucky. It is anticipated that the differences in surface transport as well as subsurface transport in a karst terrain versus those in a non-karst region would dramatically impact the data, tools and techniques required to successfully model the hydrological processes that occur in these karst landscapes. It is also expected that the interaction between the surface and the subsurface systems could differ between karst and non-karst environments. These intricacies are important in understanding the movement of stormwater pollutants in the study area.

2) **Objective II** is hence to develop a **general** procedure for predicting stormwater runoff pathways and thus improving water quality monitoring practices in karst regions using GIS technologies and spatial analysis functions. This includes the identification of GIS tools and techniques necessary to analyze the surface and subsurface stormwater runoff behaviors as well as the compilation of the common data sets that are required to fulfill the analyses.

The completion of these two objectives is expected to provide a baseline for tools, data, and spatial analysis procedures necessary for a karst community with limited resources and personals to be in compliance with stormwater mapping and monitoring guidelines set forth by the CWA and SDWA, and in turn be able to provide decision makers with better information with regard to protect water quality and public health from potential pollutants in stormwater runoff.

CHAPTER 2 BACKGROUND

This chapter discusses briefly some fields of relevance to this research, including U.S. policies on stormwater management, stormwater management issues in karst regions and the role of GIS in stormwater management and karst management. In summary, stormwater monitoring has been widely addressed in existing literature, as poor management would impact many facets of a community from environmental pollution to public health. But there are limited studies specifically on the applications of GIS technologies in developing a methodology for monitoring stormwater pollutant transport in karst regions, the main objective of this research.

2.1. U.S. Policies Regarding Stormwater Management

In 1972, the Amendments to the Clean Water Act (CWA) prohibit point source discharge into water system unless authorized. The Phase I Environmental Protection Agency (EPA) stormwater program expands the CWA in 1990. In 1996 a national water quality inventory revealed that 40% of US waters still did not meet water quality standards. This prompted EPA to issue Phase II regulations in 1999, addressing stormwater discharge (Branch, 2002). To meet these regulations, water must be sampled to realize and act to remediate stormwater runoff problems. Phase II water quality standards requires local governments to implement a stormwater management program that addresses the following six measures:

1) Public education and outreach on stormwater impacts
2) Public involvement/participation
3) Illicit discharge detection and elimination
4) Construction site stormwater runoff control
5) Post-construction stormwater management for new development and redevelopment
6) Pollution prevention/good housekeeping for municipal operations

The third measure, **addressing illicit discharge detection and elimination**, is of particular relevance to this research. In summary, the Best Management Practices (BMPs) incorporated in the Measure 3 of Phase II regulations are a set of seven practices necessary to be in compliance with Measure 3, including:

1) Develop/Implement Illicit Discharge Detection and Elimination Program
2) Establish and maintain appropriate legal authorities
3) Develop a Storm Sewer System Base Map
4) Implement illicit discharge detection procedures
5) Conduct employee cross-training
6) Provide public education
7) Establish a public reporting mechanism

The EPA (2007) recently issued a memorandum on a monitoring strategy for compliance with the CWA, saying that there are 29 categories of industry that should be looked at for runoff concerns. Guidance from Urban Stormwater Management in the

United States (National Research Council, 2008) ranked these industrial operations into three degrees (low, medium and high) of potential contamination severity. This distinguished the highest priorities for sampling due to the hazardous effects certain industrial chemicals may have on the groundwater quality.

In addition, the EPA also designates eleven categories of industry in the National Pollutant Discharge Elimination System (NPDES). These categories are used to define permitting requirements as well as the sampling standard for governments to sample 10% of each category annually in order to ensure discharge standards are being met. The eleven categories are as follows:

- **Category One (i):** Facilities subject to stormwater effluent discharge standards in 40 CFR Parts 405-471
- **Category Two (ii):** Heavy manufacturing (for example, paper mills, chemical plants, petroleum refineries, and steel mills and foundries)
- **Category Three (iii):** Coal and mineral mining and oil and gas exploration and processing
- **Category Four (iv):** Hazardous waste treatment, storage, or disposal facilities
- **Category Five (v):** Landfills, land application sites, and open dumps with industrial wastes
- **Category Six (vi):** Metal scrap yards, salvage yards, automobile junkyards, and battery reclaimers
- **Category Seven (vii):** Steam electric power generating plants
- **Category Eight (viii):** Transportation facilities that have vehicle maintenance, equipment cleaning, or airport deicing operations

- **Category Nine (ix):** Treatment works treating domestic sewage with a design flow of 1 million gallons a day or more
- **Category Ten (x):** Construction sites that disturb more than five acres (permitted in a separate section of NPDES guidelines)
- **Category Eleven (xi):** Light manufacturing (For example, food processing, printing and publishing, electronic and other electrical equipment manufacturing, and public warehousing and storage).

The industrial sites in this study are designated by the Resource Conservation Recovery Act (RCRA) because the products used by these sites include some that are hazardous and have known effects on environmental and human health (EPA, 2009). Meeting these BMPs can be challenging for many communities because of the breadth of information necessary to develop a comprehensive and cost-effective plan for monitoring waste and chemical discharge. GIS can certainly provide a number of tools capable of compiling all the variables necessary to take into consideration for stormwater quality detection and analyzing the elements to determine the best sites for monitoring stormwater discharge. Hence this thesis research mainly focuses on the roles of GIS technologies in developing an all-encompassing stormwater monitoring system to be in compliance with Measure 3, BMP 1, Detection portion of Phase II regulations set forth by the EPA. Developing appropriate stormwater monitoring plans for cities like Bowling Green, Kentucky is essential, not only to be in compliance with the EPA regulations, but also because the karst environment is so susceptible to contamination that the risks to public health are significant and need to be monitored closely so that appropriate measures can be taken if the circumstances deem themselves necessary.

Stormwater management traditionally entails surface runoff and the consequential management of runoff through Best Management Practices (BMPs), including water filtration through wetlands and slow moving (laminar) flow through the soil. The geology in karst systems, however, presents more complications to these regular stormwater management practices. The limestone rock formations are eroded by a mild carbonic acid created by the combination of water with atmospheric or soil carbon dioxide (Crawford, 1989). This slow dissolution of geology creates conduits for stormwater drainage to funnel into sinkholes and transfer directly into the groundwater system. Because of these subsurface conduits, a major concern of runoff in karst regions is that the flow is turbulent, sometimes moving as quickly as surface water flow with no or little soil filtration (White, 1988). In his study related to contaminated stormwater runoff in the Bowling Green, Kentucky, Crawford (1989) also points out that the contaminated stormwater enters directly into the karst network under the city, whereas in a scenario without the karst infrastructure, the contaminants have the potential to be filtered out by passing through the soil. The combination of contaminants in the stormwater, *e.g.* gasoline and industrial solvents, built up toxic fumes in the karst system underneath the city. The problem was so severe that the Environmental Protection Agency (EPA) had to cite two Superfund emergencies in the city between 1983 and 1989. In addition, the US Centers for Disease Control (CDC) even issued a Health Advisory for Bowling Green in 1985.

2.2. Stormwater Management in Karst Regions

Before it is possible to model accurately stormwater runoff processes on both karst surface and subsurface, it is necessary to understand the hydrological and geological properties that define a karst environment. The geology in karst regions is constructed of carbonate rocks, meaning the composition contains carbonate minerals and are easily dissolved by groundwater (Ford and Williams, 2007). Limestone and dolomite are the two types of rocks most commonly associated with karst regions. The study area around Bowling Green, Kentucky is composed of Ste. Genevieve and St. Louis Limestones (Kentucky Geological Survey; See *Section 2.5* for more detailed discussion). The formation of conduits through the limestone is dependent on a few factors including elevation changes and chemical interactions, and locations of fissures in the geology (Worthington, 2005), but when all other inputs are equal, the assumption is the pathways would form first at the deeper water levels – in essence at the location of potentiometric valleys (Worthington, 2001). The conduits in karst subsurface are often referred to as the 'grey box' where characteristics and possibly some structures are known about the system, but not everything is known about subsurface pathways and accumulation (Ford and Williams, 1989). Defining the valleys and the basins that feed into them is the impetus of the methodology, and being able to create an estimate of these features is expected to greatly enhance the ability to prepare effective stormwater runoff management plans.

In general, there are several issues that need to be taken into consideration when developing a water quality sampling network that captures area-specific characteristics. For instance, a water quality monitoring plan was created for North Georgia based on six parameters (Metropolitan North Georgia, 2003), including exit of important land use areas and suspected change, existing sites to maintain historical records, stations that represent soil and vegetation boundaries, possibly watershed exits, reasonably accessible to roads, and taking into consideration sites that would be point source pollution discharges. While Metro North Georgia does not have the complications of karst features when sampling specifically for industrial stormwater runoff, they do detail some particulars in ensuring that only stormwater is leaving industrial sites and that it does not contain additional contaminants. While Metro North Georgia and other communities in non-karst regions have developed stormwater runoff management plans, creating one for karst regions presents the challenge of turbulent infiltration into underground flow and often confusing watershed delineation because of the mismatch between surface and subsurface drainage directions. As pointed out by Stephenson, et al (1999), while there are many studies done about stormwater runoff of highways, very little literature addresses runoff to karst features and this is especially worrisome because contaminated runoff may flow directly into the aquifer without the filtering effects soil that would have on runoff in non-karst terrains. In their study, 16 samples were taken during a storm event when runoff entered three sinkholes and 11 samples were collected when water exited at a spring as the exit of the sinkholes by dye tracing. Two observations were made: 1) the peak discharge was at the same time as the peak highway stormwater runoff into the sinkhole; the peak dye concentration did not arrive at the spring for 40 minutes after the maximum discharge level. These two observations indicate that the larger discharge from the spring does not always correspond with the highest concentration of contaminant exiting the spring, assuming that water already existing in the karst features is displaced by the storm event. These observations just highlight some complications in the development of effective stormwater monitoring plans in karst regions.

2.3. The Role of GIS in Stormwater Management

Due to the geographic nature of watershed boundaries, water conduits, and impervious urban surfaces, GIS is the natural tool that should be useful for simulation and database creation for stormwater management (Sample et al, 2001). In many previous studies, the majority of the work done integrating GIS with hydrology is on large-scale natural hydrological systems using primarily raster datasets. Studies on a smaller scale using vector datasets to best fit the variability found in urban areas is less common. GIS lends itself to many aspects of the EPA's NPDES compliance because each of the nine elements addressed has a spatial component (Huey, 1998). One of those components is industrial and high risk runoff. A spatial inventory of structures associated with stormwater runoff such as storm sewers, curb inlets, etc. can be used for maintenance history and creation of a monitoring schedule and plans. The NPDES highlights the significance of impervious surfaces in the routing of contaminates into groundwater based on the case studies carried out by the California Department of Transportation (Caltrans) (Brice, 2002). As part of remedying the potential for automotive chemicals reaching water sources, Caltrans inventoried stormwater inlets from roadways and discharge points leaving the area of interest. The inventory of stormwater discharge features has allowed the GPS-collected data to be incorporated into a GIS-based permit inspection database as well as tracking the flow of water from entry to exit of the stormwater system.

Another example of the applications of GIS technologies in stormwater management is Strobl, et al's study (2006). When selecting critical water quality monitoring sampling points, they used GIS to assess hydrology, topography, soil permeability, vegetation, and land use characteristics of a watershed in Pennsylvania. The layers are weighted and an index was created for the potential surface pollution runoff for each water sampling site. It was determined that the initial four sampling points may not be the best to assess what is going on in the watershed. Instead six monitoring points are suggested based on the highest potential surface pollution runoff index.

2.4. The Role of GIS in Karst Groundwater Management

In the past decade, GIS has been gradually utilized in many fields of karst studies. For instance, an inventory of karst features was created for Southeastern Minnesota (Green, et al. 2001). The catalog of sinkholes, disappearing streams, caves and springs was developed to "*better understand landscape dynamics*". The inventory was then paired with elevation models and underlying geology rasters to assist karst management and stormwater protection on karst features with less bedrock material buffering the karst features from surface runoff (Gao, et al. 2001). In addition to the role of inventorying karst features, GIS technologies have been used to develop more advanced spatial modeling and analysis ability for karst studies. For instance in Gao et al.'s study (2001), spatial analysis methods such as nearest neighbor statistics were used to determine a pattern of likelihood of where sinkholes would occur. Overall, there are two particular areas that GIS has been mostly utilized, including the assessment of groundwater vulnerability and the groundwater flow modeling.

2.4.1. Groundwater Vulnerability

The infamous DRASTIC Model for groundwater vulnerability combines seven factors impacting susceptibility: Depth to water, Net recharge, Aquifer media, Soil media, Topography, Impact of vadose zone media, and hydraulic Conductivity of the aquifer (Aller et al, 1985). The model is a good general way of describing groundwater conditions. Further methodology was developed to adapt the DRASTIC model to accommodate a karst environment (Smith and Crawford, 1989). The adapted DRASTIC model assesses vulnerability by looking at many of the same factors that impact groundwater movement in a karst system, but further investigation is necessary to determine movement through the ground. An adapted DRASTIC model was adapted for the Barren River Area Development District (BRADD) (Croskrey, 2006). This area includes Allen, Barren, Butler, Edmonson, Hart, Logan, Metcalfe, Monroe, Simpson, and Warren Counties in Southern Kentucky. It has long been known that the karst features in this region have created complex stormwater management issues that are not found in environments without karst conditions (Crawford, 1989). Croskrey's (2006) study was significant because it used GIS to combine the contributing factors and create a groundwater sensitivity index. This information helps anticipate problem with stormwater runoff in particular sections of the BRADD.

There are two more successful cases of applying GIS in studying groundwater issues. The Edwards Aquifer, in the San Antonio region of Texas, serves as a water supply for the large city. In May 2000 tax payers voted to increase taxes to pay for the effort to protect the aquifer. GIS was used as a tool to assess the most susceptible parcels of land to aquifer contamination (Veni et al, 2001). Features like hydrogeology, karst features, and wildlife populations were taken into consideration to determine the areas in the most urgent need of protection. Another case is the assessment of the aquifer in Florida, an important natural resource to support the state's growing population. Along with the larger population, the impacts of an increasing water consumption and rising contamination of the Florida Aquifer System necessitated a survey to determine the vulnerability of the aquifer. The vulnerability assessment took four factors into consideration to determine the likelihood contamination could enter the aquifer system: soil permeability, karst features, thickness of the intermediate aquifer system, and the difference in hydraulic head (Arthur et al, 2005). Weighting the impacts of these layers, the state was divided into zones based on the susceptibility the aquifer has to contaminants. The Wekiva Aquifer in Florida was assessed for groundwater vulnerability using the same themes as the Florida Aquifer Vulnerability Assessment in Arthur, 2005 (Cichon, 2005). GIS was used to overlay rasters of each of these themes to create a weighted "*response*" layer of all of the combined inputs. The use of GIS for the Wekiva Aquifer, particularly with more refined datasets, provided a more detailed GIS-based assessment of the vulnerability over the spatial extent.

2.4.2. Modeling Groundwater Flow

Some of the origins of GIS are based on environmental applications and the need to model landscape processes accurately (Maguire, et al 2005). In the past several years, the development of ArcHydro has succeeded in combining GIS with hydrological modeling capability such as drainage, hydrography, stream networks, channels, and time series (Maidment, DR 2002). ArcHydro tools, available in ArcGIS 9.3, are mainly developed for surface water applications, but do not adequately address groundwater systems – particularly dealing with karst systems. Nalbantis, et al (2002) compared three different techniques for determining groundwater flow integrated with GIS. The first combines surface and subsurface flows, the second is a lumped parameter model, and the third uses the MODFLOW model for groundwater flow.

The Floridian aquifer is the primary drinking supply to residents of Florida, but is also very susceptible to groundwater contamination because of the karst landscape. In anticipation of a growing population a study was done in the Lake City area to best determine a wellfield site based on predicted flow, groundwater quality, and potential for contamination (Dufrense and Drake, 1999). The MODFLOW model was applied to create numerical predictions of recharge/discharge relationships in the karst aquifer. Using the data, a site was selected based on proposed pumpage and recharge values and a low vulnerability. The area for the proposed wellfield site was then tested in the field to confirm the expected results. The literature about different aspects of this study is bountiful: EPA stormwater regulation, GIS for vulnerability and structure inventory, ground water flow, etc. But there is limited to no literature about the use of GIS to predict groundwater flow pathways in a karst environment – particularly in an effort to develop a stormwater runoff monitoring plan to comply with EPA regulations. Creating a methodology capable of predicting pathways via which stormwater takes from a point pollution source, such as an industrial site, through karst terrain can assist decision makers in these karst regions prepare informed stormwater quality monitoring strategies and plans. This thesis research mainly contributes to this line of research.

2.5. The Study Area – Bowling Green, Kentucky

The City of Bowling Green is located in south central Kentucky (Figure 2.1). The city boasts the fourth largest population in the state, approximately 55,000. Several major industries are based or have satellite facilities in and around Bowling Green, including a General Motors Manufacturing Plant, Houchens Industries headquarters, Camping World, Fruit of the Loom, Trace Die Cast (manufacturing aluminum die cast automotive components), Bowling Green Metal Forming (also manufacturers of automotive components), Hill's Pet Food Manufacturing, and an industrial packaging facility for International Paper. In addition to the numerous manufacturing facilities, both Commonwealth Health Corporation (a hospital and healthcare group that serves the region) and Western Kentucky University employ many residents of the area. Many of the industries in the study area store and use chemicals that would be hazardous if leaked into water systems. In addition to industries, many local small businesses like laundromats or auto parts stores are also listed as Resource Conservation Recovery Act sites by the EPA.

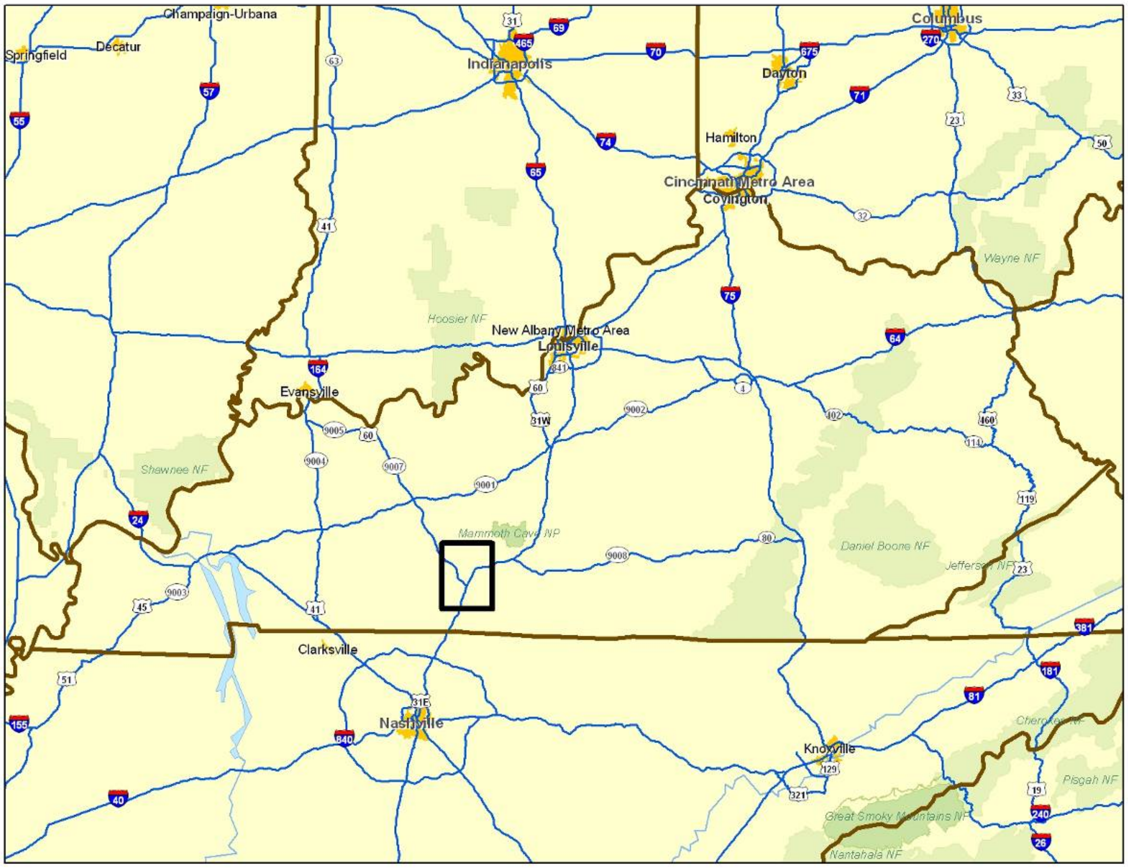


Figure 2.1 Study Area Reference Map. Note: The State of Kentucky with the area of interest rectangle in black.

The south central region of Kentucky is known for its numerous cave and karst systems, most famously that of Mammoth Cave National Park, located 30 miles northeast of Bowling Green. Figure 2.2 and Table 2.1 describe the geology in the study area. The actual geology of the study area is entirely limestone - with the exception of alluvium in the Barren River area – which the Kentucky Geological Survey categorizes as intensely karst prone. The erosion of the geology under the city by carbonic acid creates a carbonate aquifer (Crawford, 1989) where runoff that enters the subsurface quickly –

even as fast as surface water – through subsurface conduits before exiting via springs and joining the Barren River or its tributaries.

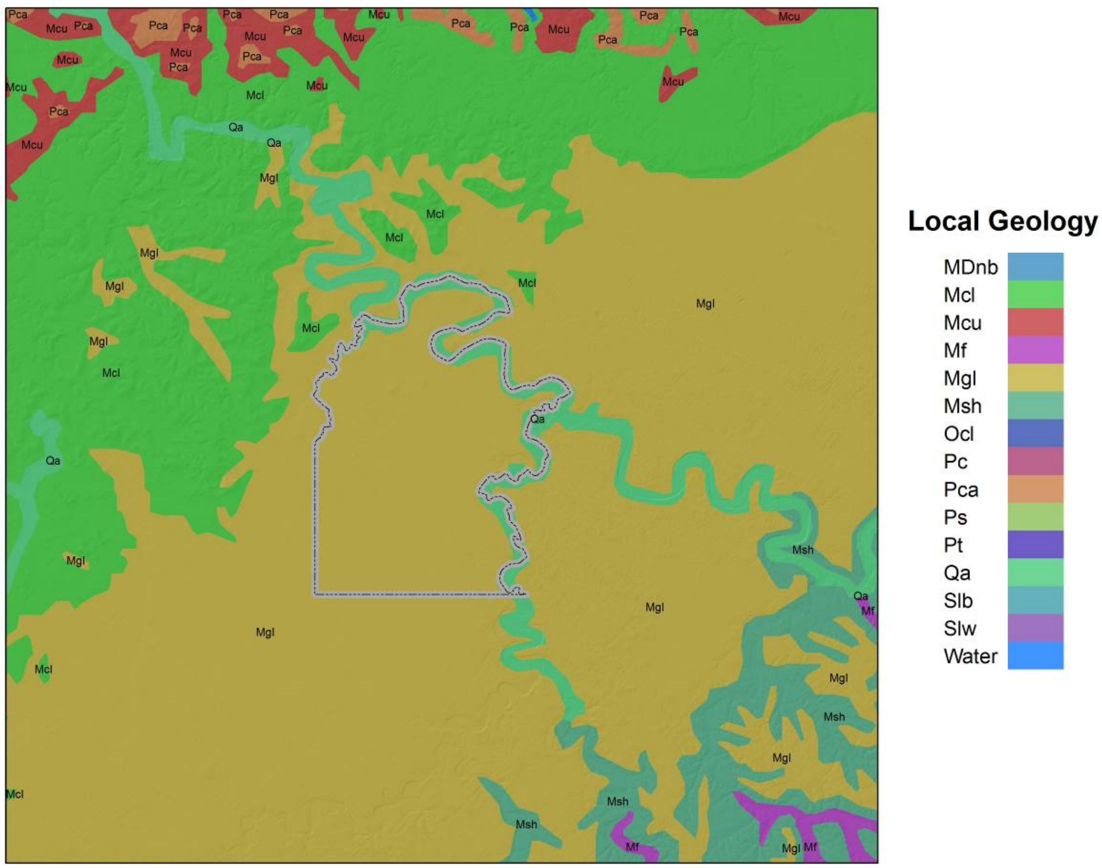


Figure 2.2 Geology of South Central Kentucky. *Source: map created with data from the Kentucky Geological Survey.* Note: Study area in a dashed line.

Label	General Geology	Karst	Geology Description	Technical Description
Mcl	Mississippian	Prone	Chesterian age rocks, lower part	Acadian foreland, proximal/medial, nonmarine/marine, unloading phase (molasse)
Mcu	Mississippian	Prone	Chesterian age rocks, upper part	Acadian foreland, proximal/medial, nonmarine/marine, unloading phase (molasse)
MDnb	Devonian	Non-karst	New Albany, Chattanooga, & Ohio Shales, Boyle Dolomite & Sellersburg Limestone [undivided]	Acadian foreland, proximal, marine, loading phase (flysch)
Mf	Mississippian	Non-karst	Fort Payne FM & Muldraugh/Renfro dolostone Mbrs (Borden FM) [undivided]	Acadian foreland, proximal, marine, loading phase (flysch)
Mgl	Mississippian	Intense	Ste. Genevieve & St. Louis Limestones [undivided]	Acadian foreland, marine, interphase (shelf carbonate)
Msh	Mississippian	Prone	Salem, Warsaw, & Harrodsburg Limestones [undivided]	Acadian foreland, marine, interphase (shelf carbonate)
Ocl	Ordovician	Prone	Cumberland Fm, Leipers & Catheys (?) LS [undivided] (southernmost Kentucky only)	Taconian foreland, distal, marine (shale/carbonate)
Pc	Pennsylvanian	Non-karst	Carbondale Formation	Alleghanian foreland, proximal, nonmarine/marine, loading phase (alluvium & coal measures)
Pca	Pennsylvanian	Non-karst	Caseyville Formation	Alleghanian foreland, proximal, nonmarine/marine, loading phase (alluvium & coal measures)
Ps	Pennsylvanian	Non-karst	Sturgis Formation	Alleghanian foreland, nonmarine/marine, linterphase (w/o shelf carbonates)
Pt	Pennsylvanian	Non-karst	Tradewater Formation	Alleghanian foreland, proximal, nonmarine/marine, loading phase (alluvium & coal measures)
Qa	Alluvium	Non-karst	Alluvium	Taconian foreland, distal, marine (shale/carbonate)
Slb	Silurian	Prone	Laurel Dolomite, Osgood Formation, & Brassfield Dolomite [undivided]	Taconian foreland, distal, marine (shale/carbonate)
Slw	Silurian	Intense	Louisville Limestone & Waldron Shale [undivided]	Taconian foreland, distal, marine (shale/carbonate)
Water	Water	N/A	Water	Water

Table 2.1 Geology Features and Descriptions in South Central Kentucky. *Source: Kentucky Geological Survey*

The study area encompasses approximately 46 square miles in Warren County, Kentucky, including most of the City of Bowling Green (Figure 2.3). The area is bordered to the east by Drake's Creek, to the west by Jenning's Creek, and to the north by the Barren River. These water bodies are natural boundaries for the study because they are the ultimate destinations of stormwater runoff and natural divides of surface and subsurface basins. The southwest boundary was determined by the extent of the well depth data available to create an interpolated potentiometric surface. This study area contains both urban and rural land uses as well as some major roadways including Interstate 65 in the east of the study area. The majority of the RCRA potential contaminant sites in Warren County are in fact within this study area. The Bowling Green, Kentucky area is ideal for this study because of the extensive amount of data available from previous research on geology and hydrology by The Hoffman Environment Institute and The Center for Cave and Karst Studies. Particularly, drywell data as well as inferred dye tracing pathways and mapped caves are available for incorporating into the study, while many communities may not have access to these types of data.

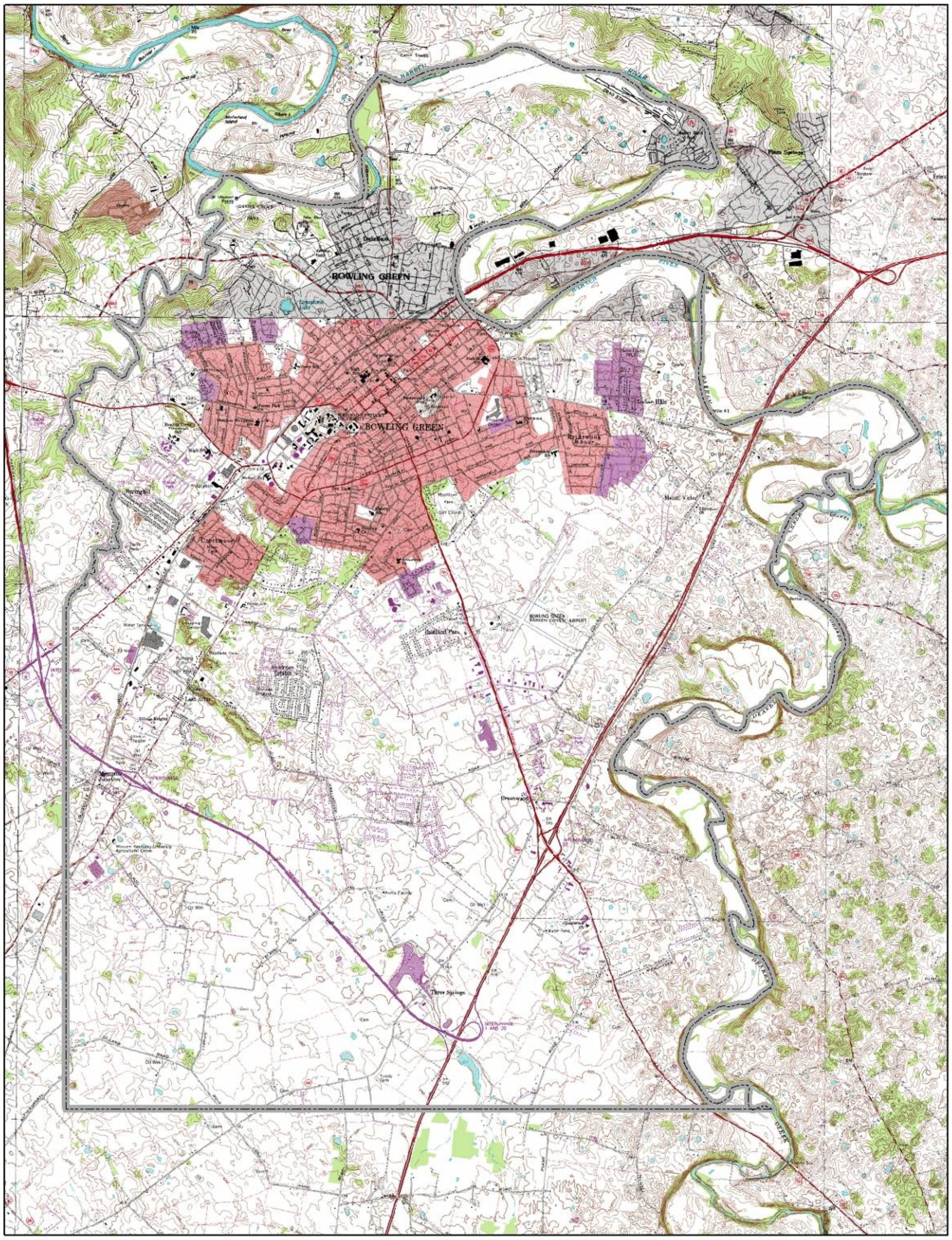


Figure 2.3 The Bowling Green, Kentucky Area. *Source: USGS topographic maps: Bowling Green North, Bowling Green South, Bristow, and Polkville 1:24,000 quads for the State of Kentucky.* Note: Study area in grey dashed line.

CHAPTER 3 METHODOLOGY

This chapter discusses the general procedure adopted in the study, on the basis of a conceptual model of stormwater pollutant transport in typical karst regions such as Bowling Green, KY. The outputs of spatial modeling mainly include stormwater surface runoff pathways from the Resource Conservation Recovery Act (RCRA) sites to their respective injection points, such as drywells and other conduits, into subsurface and via groundwater conduit pathways to surface output points, such as springs, where the runoff exits subsurface and reemerges joining surface streams. The aim is to establish the linkages among the RCRA potential containment sites and surface output points for the purpose of developing more informed stormwater sampling process. The chapter is organized as follows: the conceptual model is introduced in Section 3.1, while the following three sections provide the detailed discussions on each of the three components of the conceptual model, focusing particularly on the issues related to data compilation, GIS techniques and spatial modeling processes.

3.1. Conceptual Model

In this research, spatial modeling of stormwater pollutant transport in karst regions can be summarized with a conceptual model, comprised of three components, **Surface Input**, **Subsurface Transport**, and **Output to Surface** (Figure 3.1). The **Surface Input** models how the pollutants are transported along with stormwater runoff from potential containment sites across the surface to injection points. To achieve this, the stormwater runoff surface pathway ought to be identified from each site to its injection point in the same basin, termed in this study as "*sinkshed*", where stormwater collects. It is at injection points, such as drywells, swallets, karst windows, sinkholes, etc, where the stormwater runoff enters to subsurface. The **Subsurface Transport** then models how pollutants move with stormwater through underground conduits. The critical tasks include the delineation of subsurface basins, the inference of subsurface conduit pathways, and the identification of the connection of each injection point with its **Output to Surface** sites, such as springs, karst windows etc. These **Output to Surface** sites are the probable stormwater sampling sites. In the end, the connection among RCRA sites and sampling sites can consequently be established to assist the selection of stormwater sampling sites and to support the development of informed sampling strategies and plans.

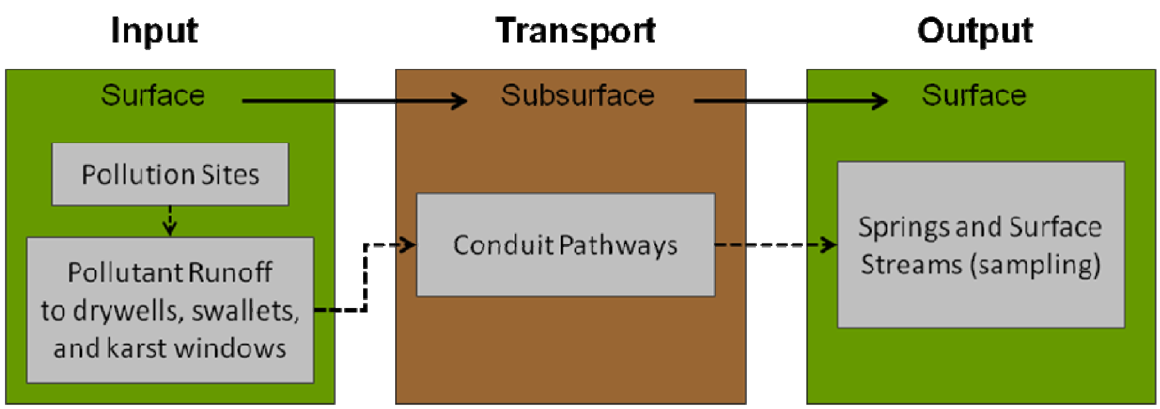


Figure 3.1 A Conceptual Model for Stormwater Pollutant Transport in Karst Regions

There are a few assumptions and defining characteristics about the study area that would need to be incorporated in any future applications using the conceptual model: 1) The first characteristic of the study area is that surface streams, such as Barren River in this study area, is not a losing stream and that ultimately all runoffs within the study area end in surface streams via springs; 2) Also, there are no known karst conduits that transport water underneath surface streams so that surface water system is the end of stormwater transport system.; 3) The third assumption is that all of stormwater runoff transported through the groundwater system exits only via surface springs. There are other karst features, such as seeps, where water may exit the groundwater system by slowly leaking between fissures in rock formations. These features are not taken into consideration in this study because of the low volume of water exiting through these features as well as with low velocity; 4) The forth assumption is that stormwater runoff occurs during storm events that cause the soil to be saturated. In this way, any runoff is not going to be filtered through the soil system, but rather funnel directly into the karst groundwater system; 5) The presence of epikarst is acknowledged in the terrain, however, this study does not address the vertical movement. Rather, it considers the horizontal movement through the conduits below the epikarst. The epikarst, or the topmost layer of the karst geology strata, is usually comprised of vertical fissures and functions to store moisture or serve as conduits that transport runoff directly into the underlying karst system where more of the transport takes place (Klimchouk, 2003). 6) The assumption is made that the water table measurements acquired from the well depths are representative of dry, low-flow conditions. 7) Lastly, this study is intended to represent phenomena occurring in unconfined aquifers.

From this conceptual model, specific issues can be further addressed with regard to data compilation and GIS technique requirements (Figure 3.2). Detailed discussions on these issues are presented in the next 3 sections. In summary, the conceptual model replicates a **generalized** physical process that pollutants are likely to be transported with stormwater runoff in Bowling Green, Kentucky area. One of the key objectives of this research is to develop a **general** procedure in GIS context that can be adopted by the communities in other karst regions. Hence the procedure must have the ability to estimate stormwater runoff pathways accurately enough, on both surface and subsurface, without the extensive cost of the conventional techniques, such as dye tracing, cave map and surveying, etc. Therefore, when adopted by other communities in need of a monitoring plan, their physical characteristics must be similar to those of the study area and the same assumptions discussed above must be made as well.

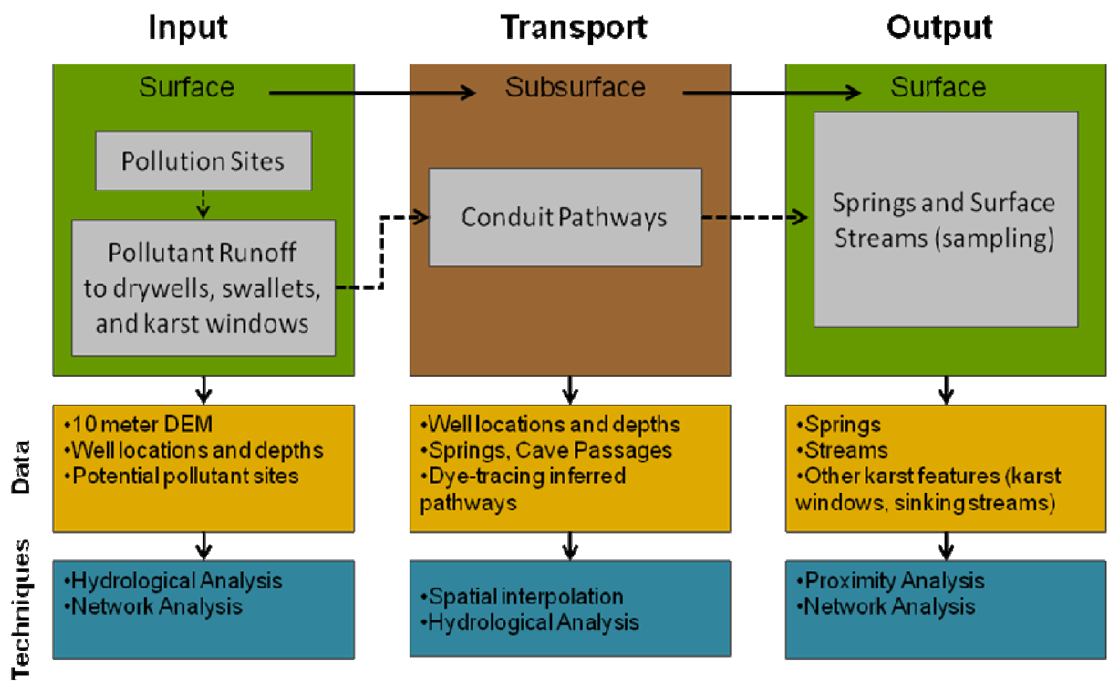


Figure 3.2 An Extended Model for Stormwater Pollutant Transport in Karst Regions

3.2. Surface Input

The Surface Input component of the conceptual model focuses on how stormwater runoff carries pollutants from potential pollution sites, here the RCRA sites, across the terrain to their corresponding injection points on surface (Figure 3.3). The injection points include drywells, swallets, karst windows as well as the lowest points downhill from the RCRA sites in the same sinksheds. These injection points are the vertical conduits via which stormwater runoff enters subsurface. Data needed for modeling surface input include an elevation surface of the study area, the locations of potential pollution sites, and the locations of vertical conduit features (drywells, swallets, karst windows, etc.). Two categories of GIS techniques are critical, hydrological analysis and network analysis. The tools of hydrological analysis are essential to create sinksheds as well as surface runoff pathways while the purpose of network analysis is to identify the closest downhill injection point for each RCRA site.

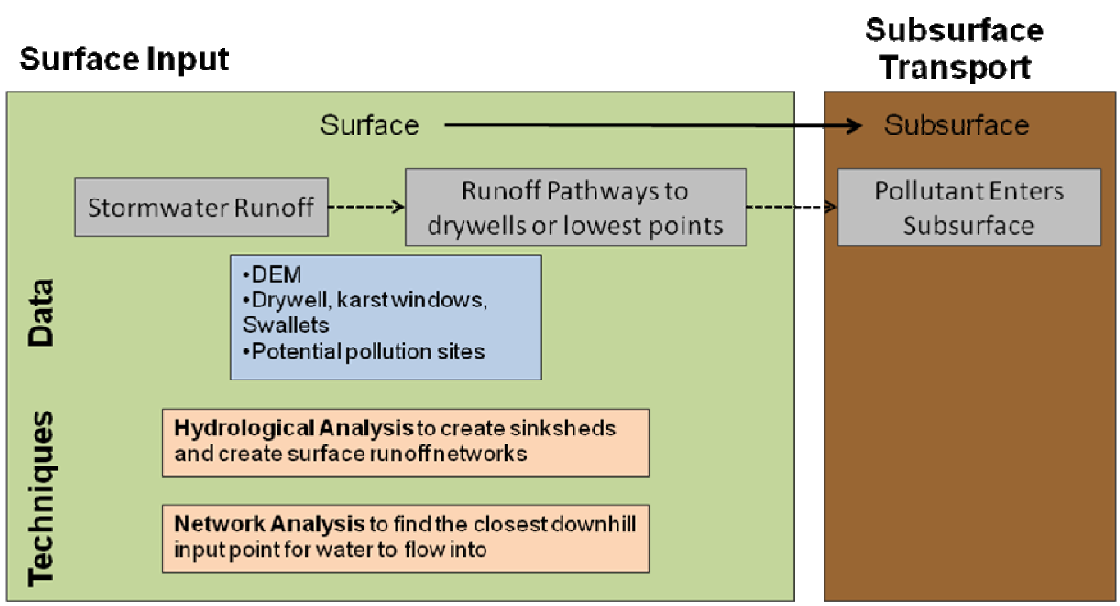


Figure 3.3 Surface Input Component

3.2.1. Hydrological Analysis

A Digital Elevation Model (DEM) surface layer is needed as an input for modeling the behavior of surface stormwater runoff. Normally in non-karst regions, DEM surfaces would be "*filled*", that is, to have the sinks removed from the raster, so that the surface runoff pathways would be created smoothly across entire area. However, that is not the case in karst regions, where the depressions and sinks are actually the significant features of the karst terrains. In order to determine surface runoff pathways via which stormwater would flow from potential contaminant sites to their corresponding injection points, the sinks must not be filled at all and instead the basin surrounding each sink, that is, **sinkshed**, must be identified for further analysis.

To illustrate the basic procedure for delineating sinksheds where stormwater runoff accumulates, geoprocessing tools in Hydrology Toolset of ArcGIS 9.3 Spatial Analyst toolbox are used in this thesis (Figure 3.4). The first step involves the generation of a Flow Direction Raster using the Flow Direction Tool with a DEM as input. Each cell of the Flow Direction Raster contains the direction at which a cell would be likely to move (in fact, each cell moves to its neighboring cell with the smallest elevation in the Flow Direction Tool). Using this Flow Direction Raster as input, Flow Accumulation Tool then produces a Flow Accumulation Raster, denoting the number of cells that flow into a single cell, while Sink Tool identifies the sinks. Next, both Flow Accumulation Raster and Sinks Raster are used as input for Snap Pour Points Tool in order to locate the cells with the highest accumulation. Snap Pour Points Tool then simply snaps the Sinks Raster to the highest accumulation cell within a certain predefined distance. Since the sinks are simply derived from the DEM layer, the pour points are assigned to be associated with the closest cell to them, meaning that the input distance for snapping is set to zero. Basins are then created using the Watershed Tool with both Flow Direction Raster and Snapped Sink Raster as input. In the last step, the basins in raster format are converted into polygons of sinksheds using the Raster to Feature conversion tool. Figure 3.5 shows some examples of such output sinksheds created in ArcGIS 9.3 for the study area. These polygons represent the areas that collect surface stormwater runoff in the study area.

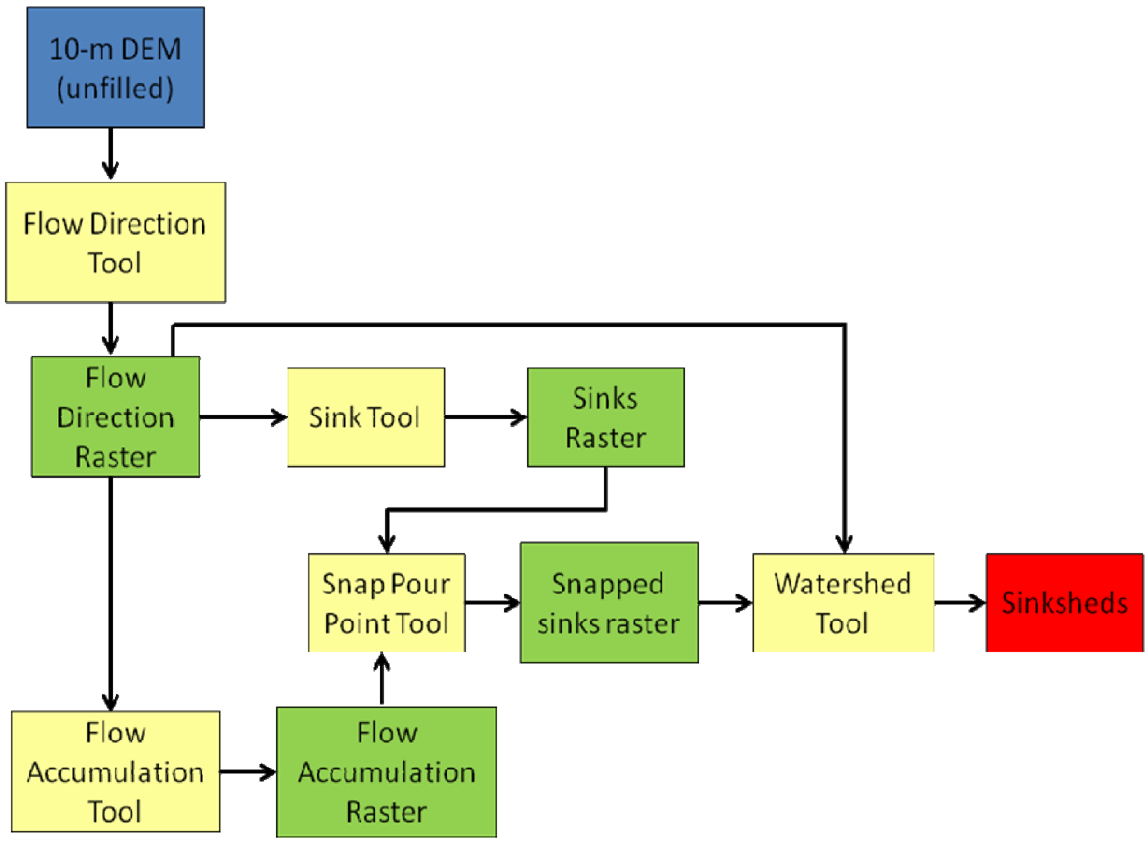


Figure 3.4 The Procedure to Create Sinksheds from DEM.

Note: blue rectangle denotes the input dataset; red rectangle denotes the output dataset; green rectangles are intermediate datasets while yellow ones represent the hydrological tools used. The same color symbology is used for all flow charts in this thesis.

Once the sinksheds are available, surface runoff pathways can be formed for each sinkshed using the Stream Order Tool with Flow Direction Raster and Flow Accumulation Raster as input (Figure 3.6). Stream Order Raster then can be converted to vector format, that is, Stream Runoff Pathways. In this research, we are only interested in the sinksheds with one or more RCRA sites inside. So only the stormwater runoff pathways within these sinksheds are selected for further analysis. This strategy is adopted simply to minimize the size of pathway dataset and thus reduce analysis time. Figure 3.7 includes only the sinksheds with one or more RCRA sites (stars) inside as well as the selected surface runoff pathways. At this point, the runoff routes are visually identifiable from RCRA sites to their lowest points in the same sinksheds (Figure 3.7).

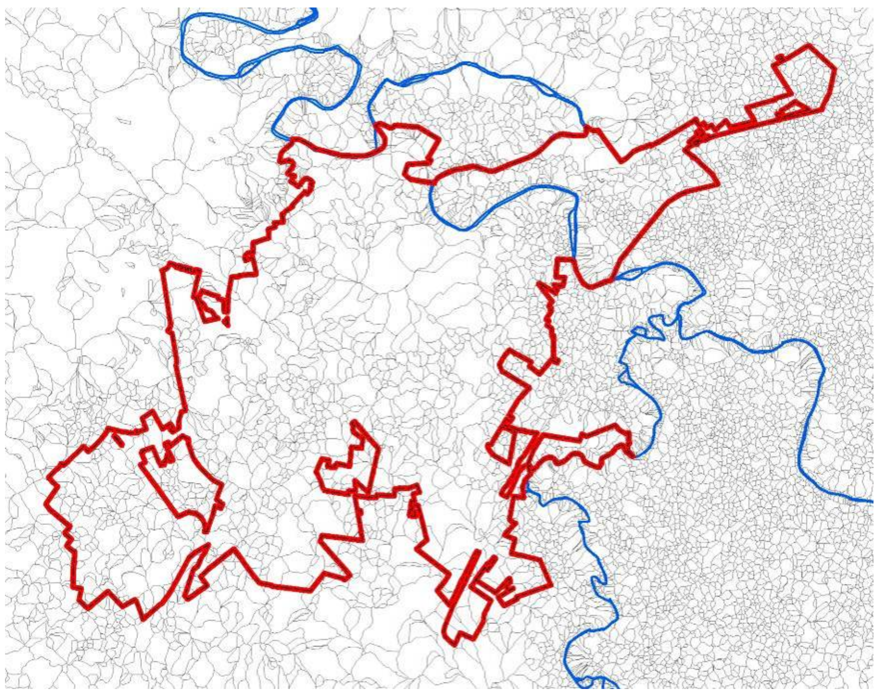


Figure 3.5 Sinksheds Identified in the Study Area

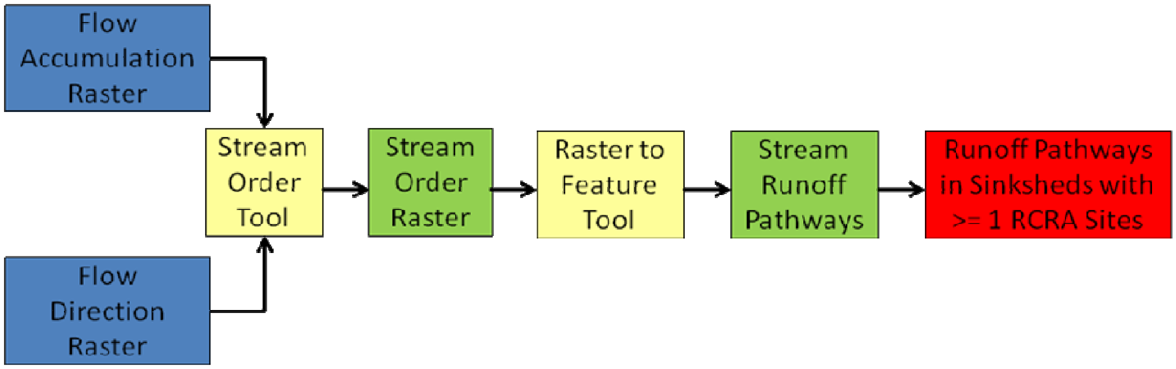


Figure 3.6 The Procedure to Create Surface Stormwater Runoff Pathways

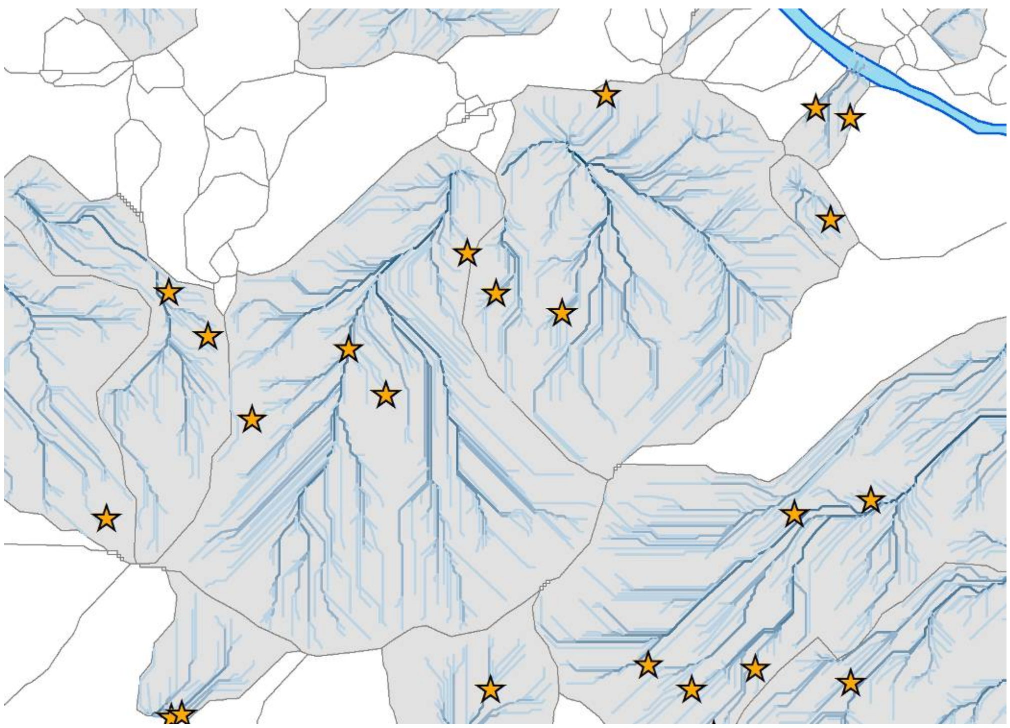


Figure 3.7 The Surface Stream Networks within Sinksheds Containing RCRA Sites

The next step is to connect each RCRA site with its closet downhill injection point, where the pollutants from a RCRA site are most likely to enter subsurface with stormwater. There are two types of potential injection points on surface: physical features, such as drywells, karst windows, swallets, and lowest points of sinksheds. In normal circumstance, surface stormwater runoff would directly plunge into subsurface when running into a downhill drywell, karst window, or swallet along the pathway. However if there are no such physical features downhill, the lowest point(s) of a sinkshed would be the injection point(s) in that they would most likely be the locations of sinkholes or the points of infiltration where runoff stormwater settles. Figure 3.8 depicts the process of using spatial join and selection operations to determine the lowest point(s) in each sinkshed. To identify the lowest point(s) of each sinkshed, all cells in the DEM surface must be converted to points with elevation attributed to them. In practice using ArcGIS 9.3 though, the DEM must be converted from Floating Point type to Integer data type because it is the format required to run the Raster to Point Tool. The floating point to integer raster conversion can be completed using the Int Tool in ArcGIS 9.3 Spatial Analyst toolset (Figure 3.9). Depending on the spatial resolution of the DEM layer, sometime a larger cell size could be used in order to reduce the number of output point features when converting floating point DEM to integer DEM.

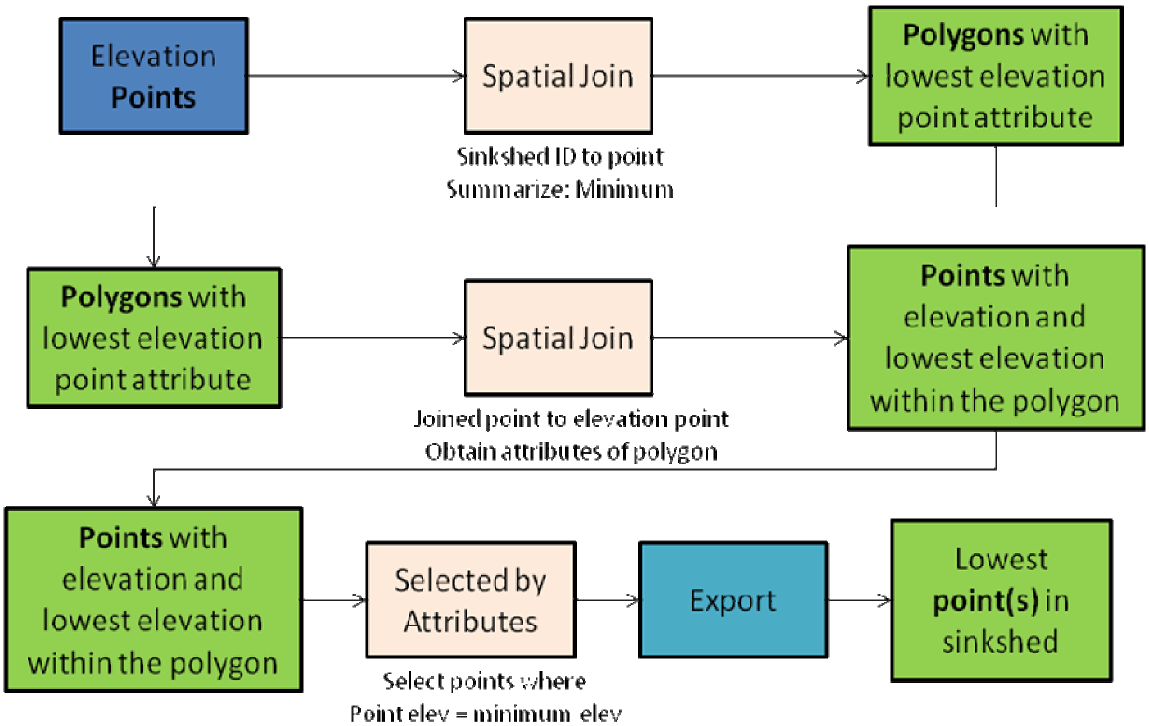


Figure 3.8 The Procedure to Identify Lowest Points in Each Sinkshed

Once the elevations points are converted, all those in the sinksheds with no RCRA sites must be excluded to reduce the data size and analysis time. A spatial join can then be implemented to join each sinkshed polygon with elevation point features within it. In addition, with the "*minimum*" numeric summary option checked, as shown in the screen capture of the spatial join dialog window in Figure 3.10, spatial join operation can produce a minimum statistics of the elevation values within each sinkshed during the process. Next, the minimum summary, that is, the lowest elevation value within each sinkshed polygon, can be joined back to the elevation point features. This time, spatial join must be completed so that each point is assigned with the lowest elevation value within each sinkshed. Lastly, the point features with their own elevation values the same as the lowest elevation values of sinksheds can be selected. These selected points are indeed the lowest points in each sinkshed. Keep in mind that there could be multiple lowest points (all with the same lowest elevation value) in some sinksheds.

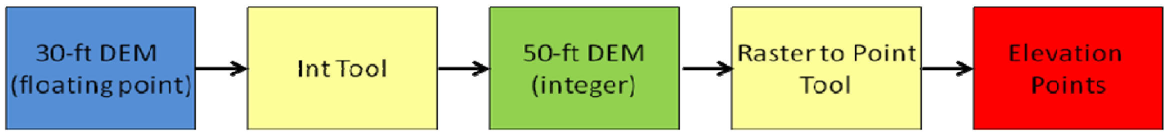


Figure 3.9 The Procedure to Create Elevation Points from DEM

3.2.2. Network Analysis

When sinkshed layer and surface runoff pathway layers are ready, the next step is to predict the probable route from each RCRA site to its closest downhill injection point within the same sinkshed. Again only the runoff pathways inside the sinksheds with one or more RCRA sites are considered. Figure 3.11 lists the main settings used in network analysis. Prior to network analysis, a runoff pathway network must be first created using surface runoff pathway layer in ArcCatalog. The default settings are used for most of the steps with the exception of setting evaluators. But in Evaluator dialog (Figure 3.12), the traverse distance at From-To direction (downhill) is set to the actual length of each pathway while that at To-From (uphill) is assigned a very high constant value, *e.g.* 10,000,000. Via this, runoff would be "*forced*" to move only downhill by weighting uphill direction so high and making it so costly to move in the uphill direction.

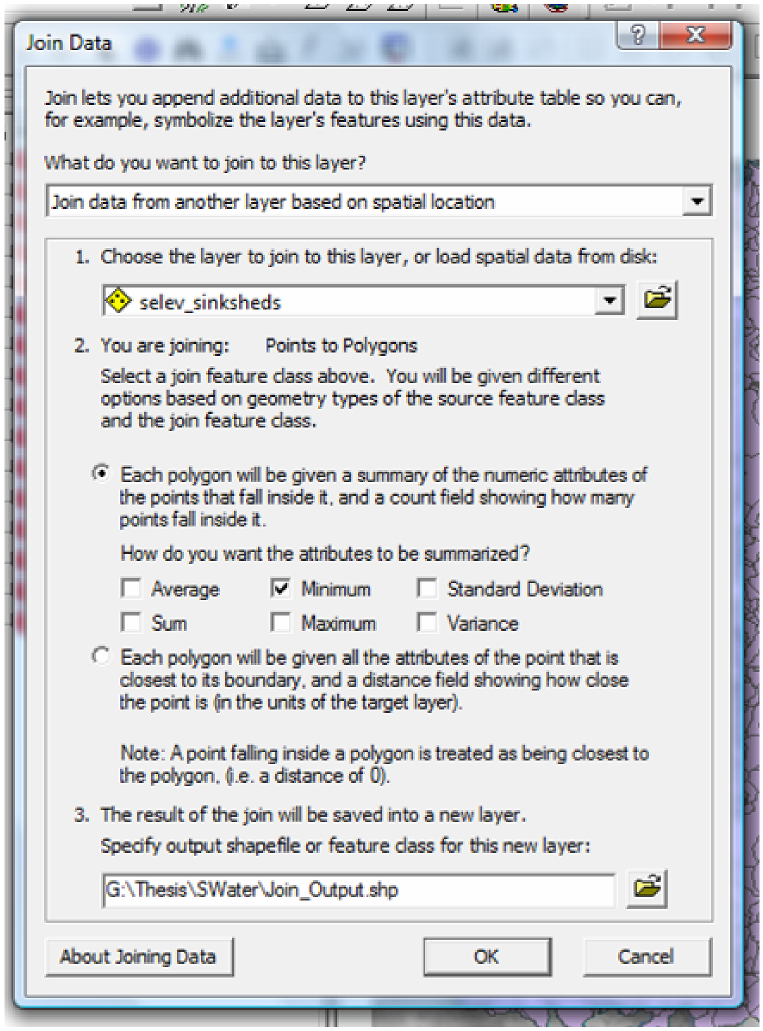


Figure 3.10 The Dialog Window for Spatial Join of Elevation Points to Sinksheds

Once a surface runoff pathway network is created, network analysis can then be carried out in ArcMap (Figure 3.11). In the Network Analyst Toolbar, a new Closest Facility Analysis (CFA) task must be created to determine the closest “*Facility*” to an “*Incident*”. In this case, the “*Facilities*” are injection points while RCRA sites are the “*Incidents*”. In real world, stormwater is most likely to enter subsurface as soon as running into a downhill physical feature as shown in Figure 3.13. Only when there are no downhill features at all, sinkshed lowest points can then become injection points where stormwater can also infiltrate through rock fissures (Figure 3.14). Hence, two separate network analysis processes must be conducted in sequence. The first process uses the actual physical features, *e.g.* drywells, karst windows and swallets, as the "*Facilities*" to create "*Routes*" (aka surface runoff pathways) from RCRA sites, while the second process uses sinkshed lowest points as "*Facilities*". Via these runoff pathways, the connection between each RCRA site and its respective injection point thus can be established.

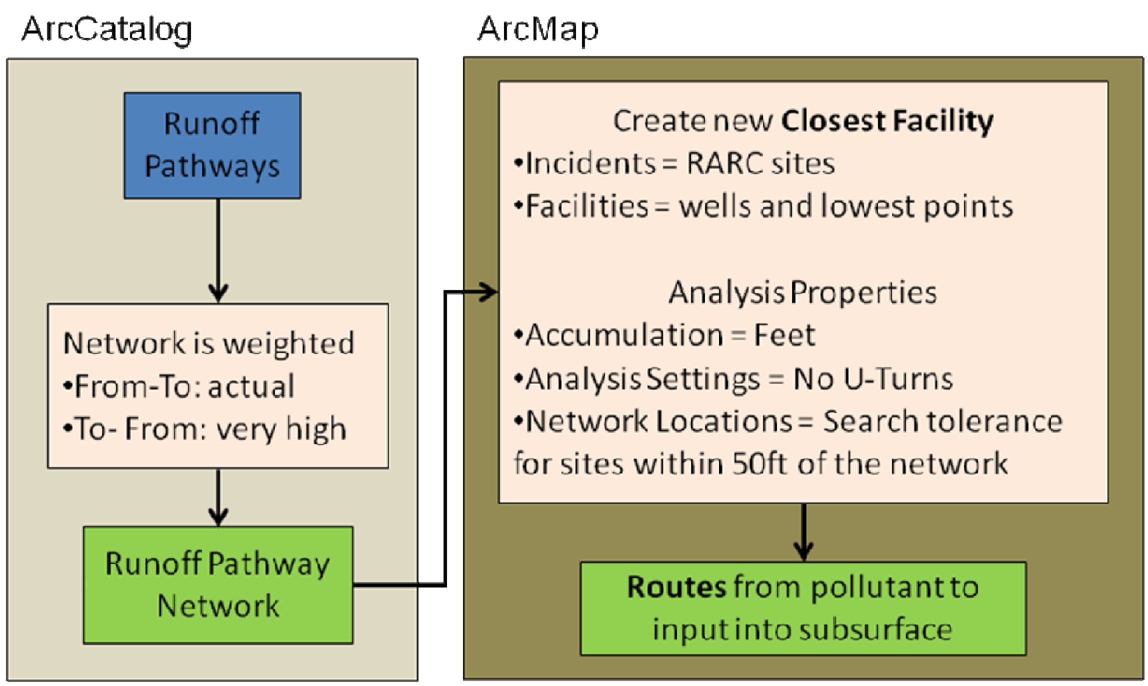


Figure 3.11 The Settings in ArcCatalog and ArcMap for Creating Runoff Network

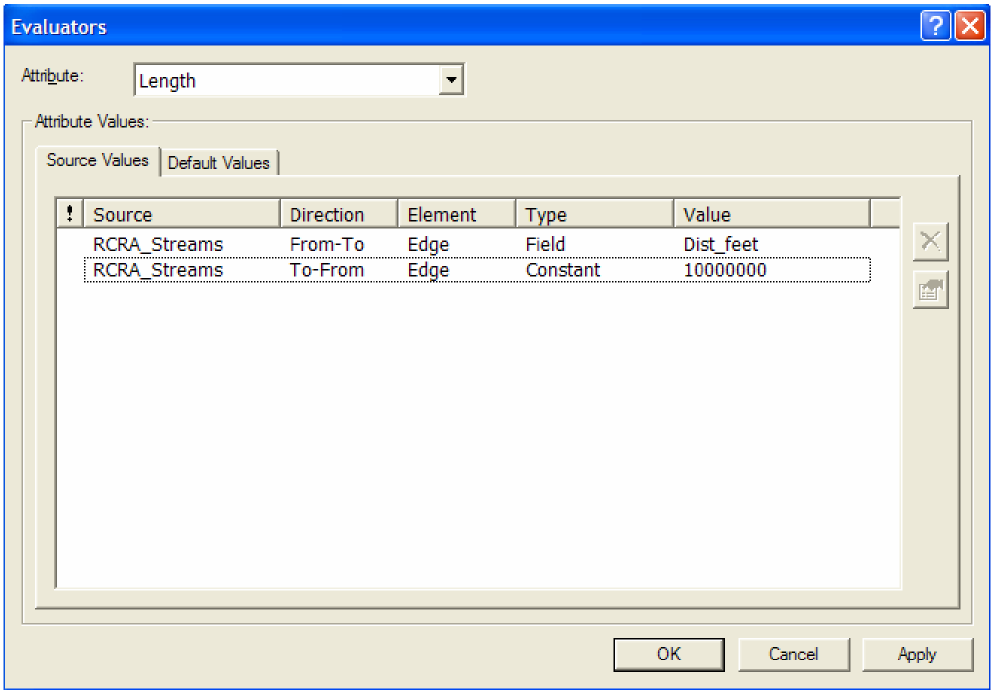


Figure 3.12 The Evaluator Settings Used to Create Runoff Pathway Network

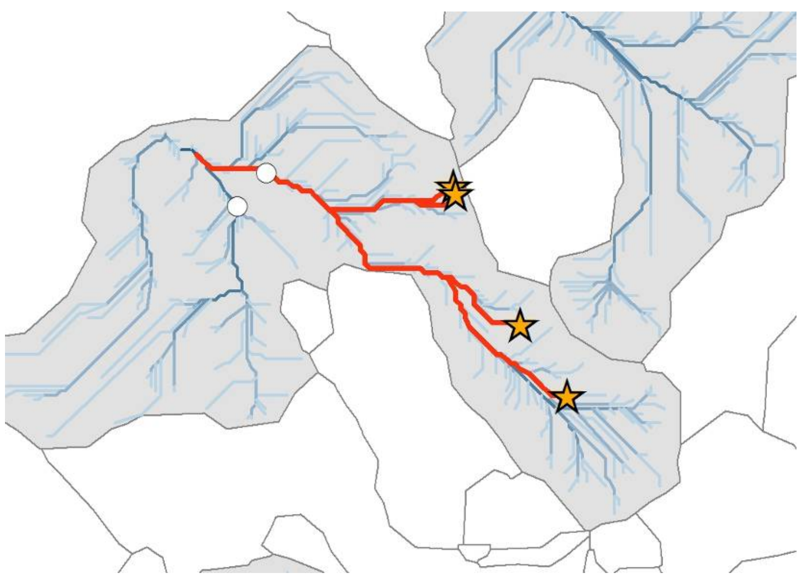


Figure 3.13 Stormwater Runoff Route from RCRA Sites to a Downhill Swallet

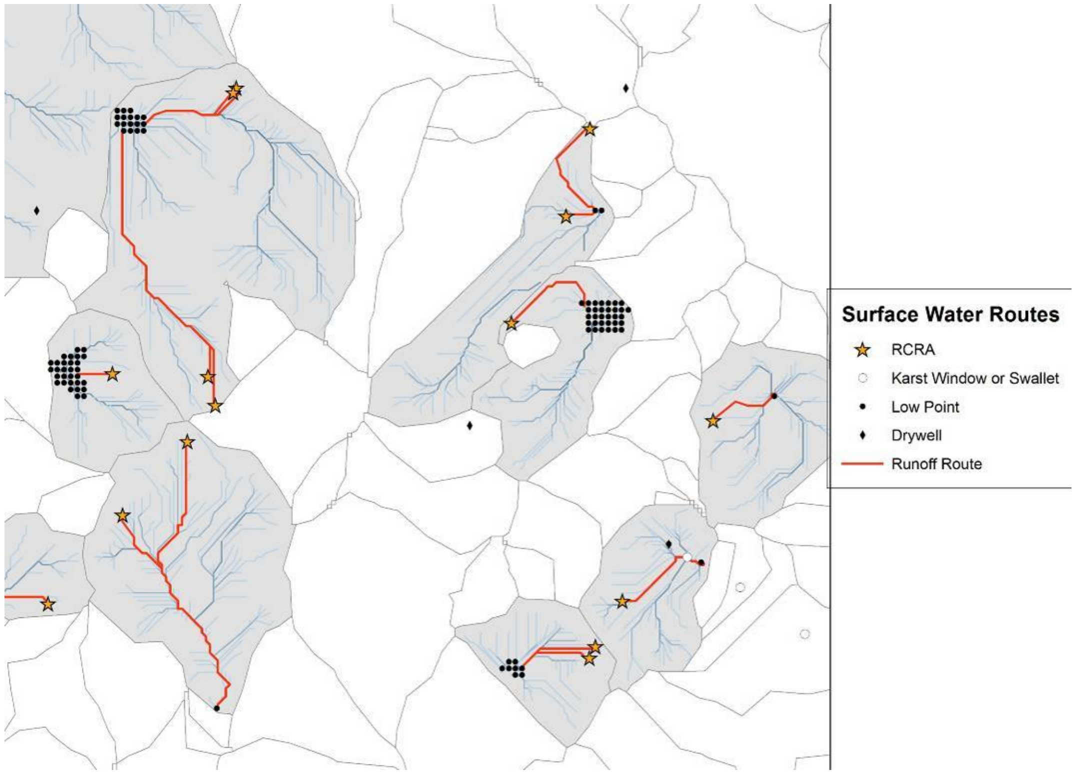


Figure 3.14 More Examples of Stormwater Runoff Routes from RCRA Sites

3.3. Subsurface Transport

Subsurface Transport component models the movement of pollutants with stormwater via underground conduits after entering subsurface at injection points. The purpose is to determine how stormwater transport pollutants between injection points, through subsurface conduits, to where it exits subsurface at output sites such as springs and backs to surface streams (Figure 3.15). The essential data in Subsurface Transport component include injection points (*e.g.* drywells, swallets, karst windows, sinkshed lowest points, etc.), well depth and locations, spring locations, surface streams, and DEM layer. Two categories of GIS techniques are useful to predict subsurface conduit pathways, Spatial Interpolation and Hydrological Analysis. The spatial interpolation is to estimate groundwater table, that is, potentiometric surface, while hydrological analysis is used to predict subsurface conduit pathways from injection points to output sites, such as springs, based on the estimated groundwater potentiometric surface.

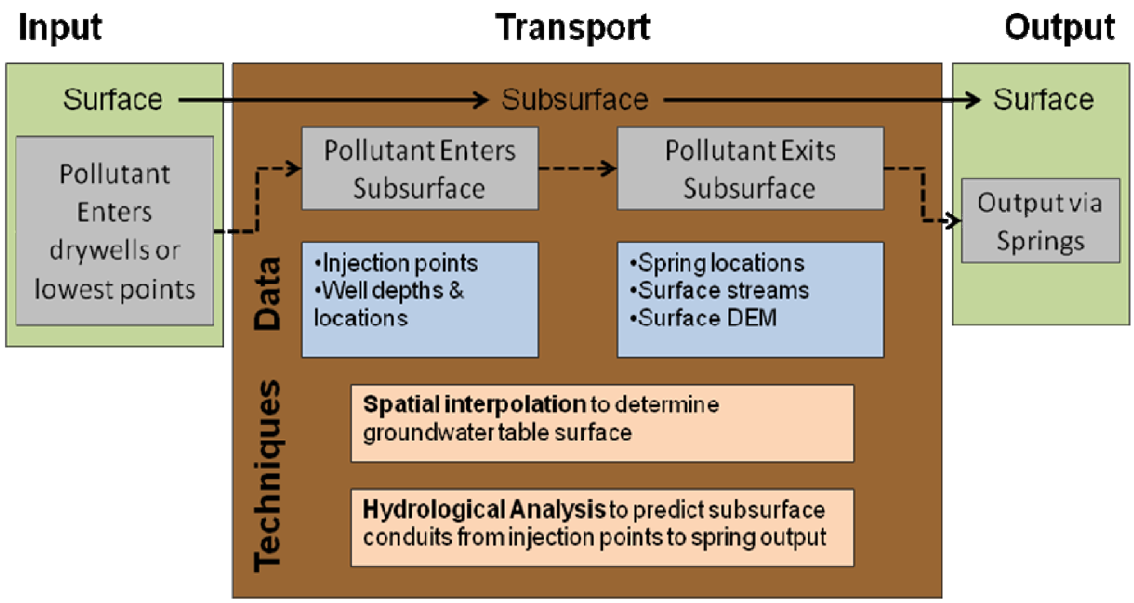


Figure 3.15 Subsurface Transport Component

3.3.1. Spatial Interpolation

The spatial interpolation technique (SI) must be used to derive a groundwater potentiometric surface. The Geostatistical Wizard in ArcGIS 9.3 Geostatistical Analyst Toolset offers a variety of SI methods for predicting surfaces from a set of known points. In our case, the known groundwater elevations include the groundwater elevations taken at drywells, the surface elevations of spring features (*i.e.* the point and elevation where groundwater reemerges from subsurface), and surface stream elevations. The groundwater elevations taken at drywells and the surface elevations of spring features are used for interpolation process directly (Figure 3.16). The challenge here is to find the proper interpolation method and set the right parameter values that are best suited for estimating potentiometric surface. After considerable amount of experiments, Local Polynomial Interpolation (LPI) with a power of 2 is recommended. One of the benefits of LPI is that users can weigh the influence of global property (universal trend) and local (neighborhood) effects. Conceptually, a potentiometric surface is usually impacted by water table (represent the universal trend and often exhibit the shape of power 2 convex) and rock fractures (local effects). This fits well with LPI. Figure 3.16 shows a preview of a potentiometric surface by LPI with 20% global effects and 80% local effects, using well groundwater elevations only.

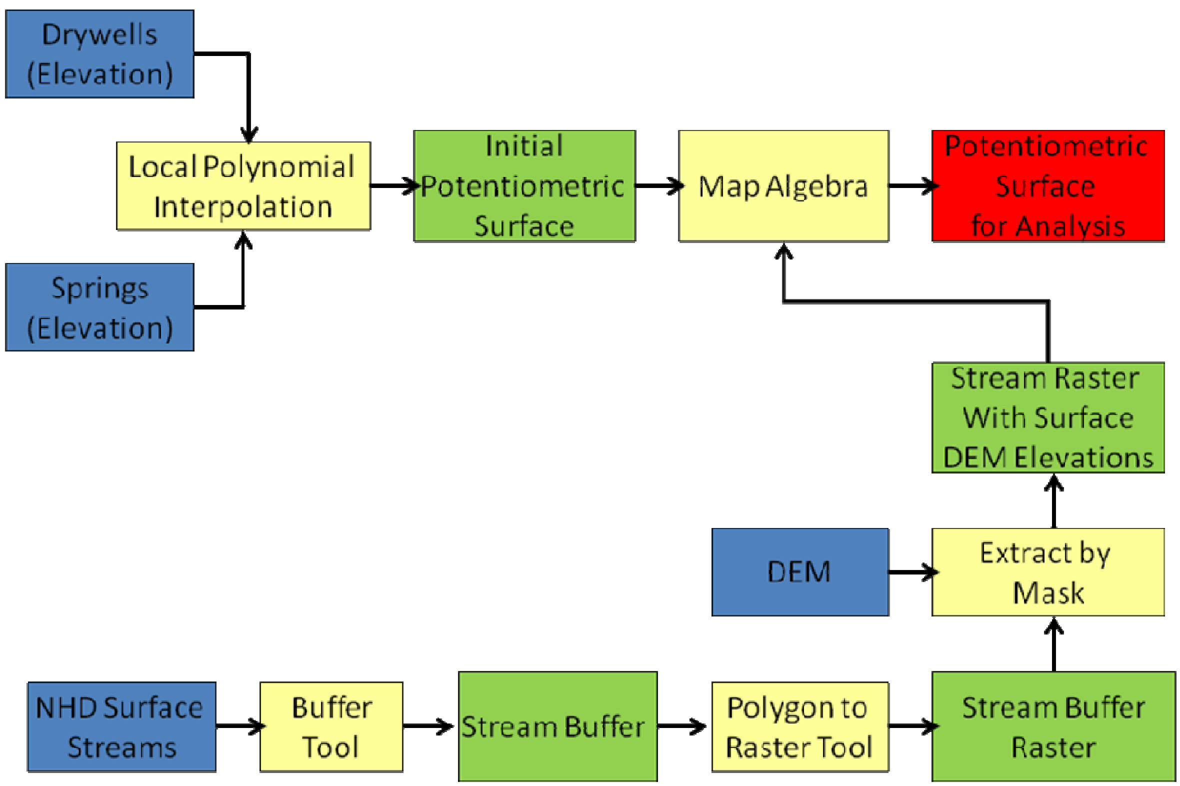


Figure 3.16 The Procedure to Create Potentiometric Surface

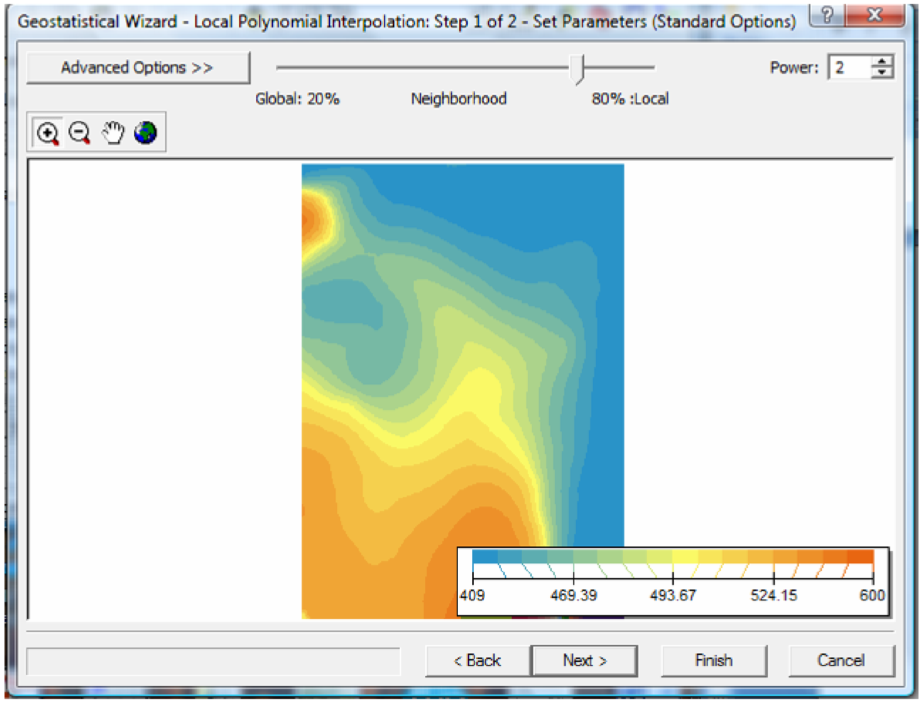


Figure 3.17 A Preview of Potentiometric Surface Created with LPI

As pointed before, the elevations of surface streams, basically the ultimate destinations of all stormwater runoff, can provide additional groundwater level data for improving the estimation of potentiometric surface. In this regard, the elevations of surface streams must be "*burned in*" to the preliminary potentiometric surface (Figure 3.16). In U.S., the commonly available stream features are the line shapefiles from that National Hydrologic Dataset (NHD). To implement the above strategy, a buffer zone can be created around the streamlines with a certain predefined distance and this buffering zone must be converted to raster format using the Polygon to Raster Tool. The streams buffer raster layer can then be overlaid on top of surface DEM layer to extract the surface elevations of the streams, as shown in Figure 3.18.

At this point, two raster layers have been created: the interpolated potentiometric surface and the surface DEM elevation raster extracted around surface streams (an example is shown in Figure 3.18 and with a 120 feet buffer zone). The next step is to merge these two rasters to create the final potentiometric surface for predicting subsurface conduit pathways via which stormwater is likely to travel. To merge them, or in essence to "*burn in*" surface stream elevation to potentiometric surface, the Single Output Map Algebra Tool can be used in the Spatial Analyst Toolset of ArcGIS 9.3. In the Map Algebra Tool, a merge function is used to build a map algebra formula: **Merge([Stream Elevation Raster], [Potentiometric Surface Raster])** to superimpose the surface DEM elevations into the potentiometric surface, as shown in Figure 3.19.

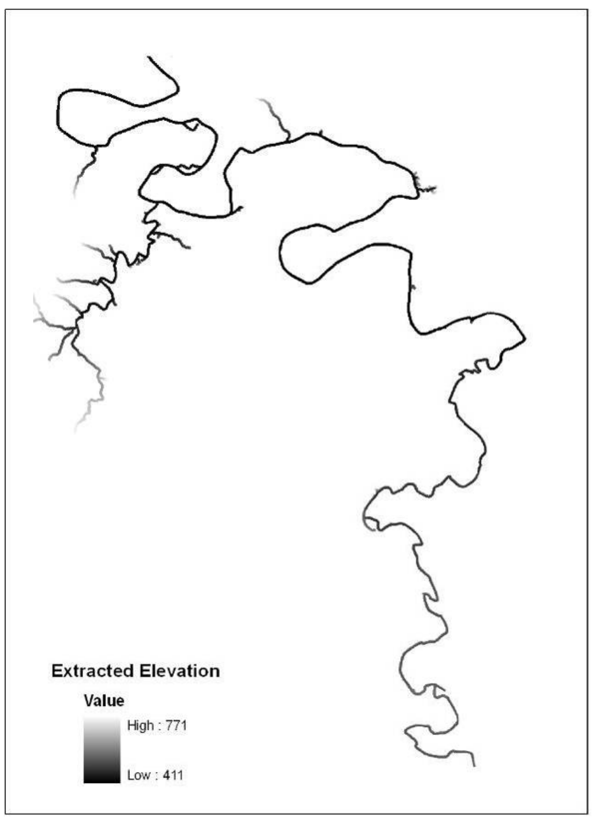


Figure 3.18 An Example of Surface DEM Extracted Around Streamlines

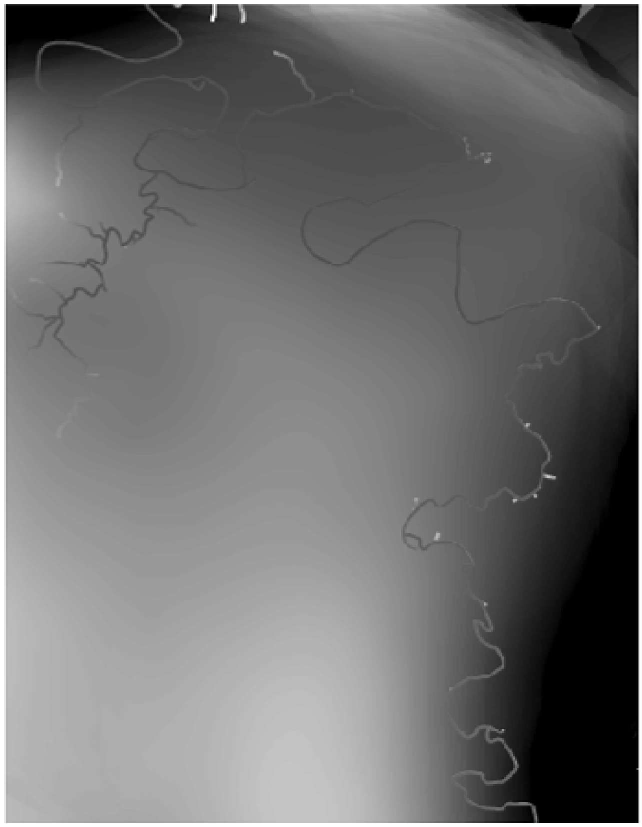


Figure 3.19 An Example of Predicted Potentiometric Surface with “Burned in” Surface Stream Elevations

3.3.2. Hydrological Analysis

The hydrological analysis procedure (Figure 3.20) in Subsurface Transport is similar to that used in the Surface Input component (Figures 3.4 and 3.5), except that the input raster is a potentiometric surface and sinks in the potentiometric surface area unwanted and must be removed first using the Fill Tool (available in the Hydrology Toolset of Spatial Analyst Toolbox). Using the filled potentiometric surface as input, the Flow Direction Tool creates a Flow Direction Raster with each cell storing the direction at which stormwater is likely to flow to a neighboring cell. Then the subsurface basins for each output spring point can be predicted using the Watershed Tool with the Flow Direction Raster as input. The spring locations must be snapped to the cell with the lowest value within a certain predefined distance (*e.g.* 720 feet used in the case study). This step allows for some unaccounted variability in the terrain, while still capturing the general undulations of potentiometric surface. These subsurface basins can then be used to infer underground conduit pathways via which stormwater would move, as shown in Figure 3.21, and the output surface springs associated with injection points.

3.4. Output to Surface

Once subsurface conduit pathways are ready, the connections among the RCRA sites and their output springs can be established by overlaying subsurface basins with both injection points and springs. The sampling sites can then be selected by examining other criteria such as their proximity to roadways and to each other. In addition, it is also possible to pick springs where the samples can reflect stormwater runoff from similar land use classifications in order to better understand what areas are contributing to contaminant levels and remedy problems or target better education on water quality issues. The EPA categorizes potential pollution sources into eleven different categories. The categories (described in Chapter 2) distinguish between different types of storage and processing activities associated with hazardous materials. The map in Figure 3.22 symbolizes the RCRA sites based on the NPDES permitting categories. Understanding which categories of pollutants output at sampling sites can be very useful in setting the sampling priority and planning what types of pollutants should be sampled at each sampling location.

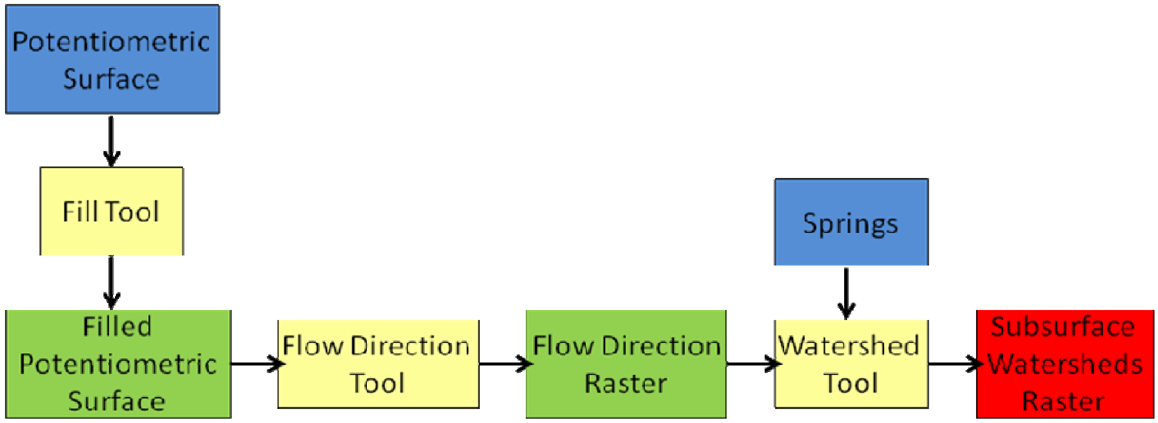


Figure 3.20 Procedure to Create Subsurface Watersheds

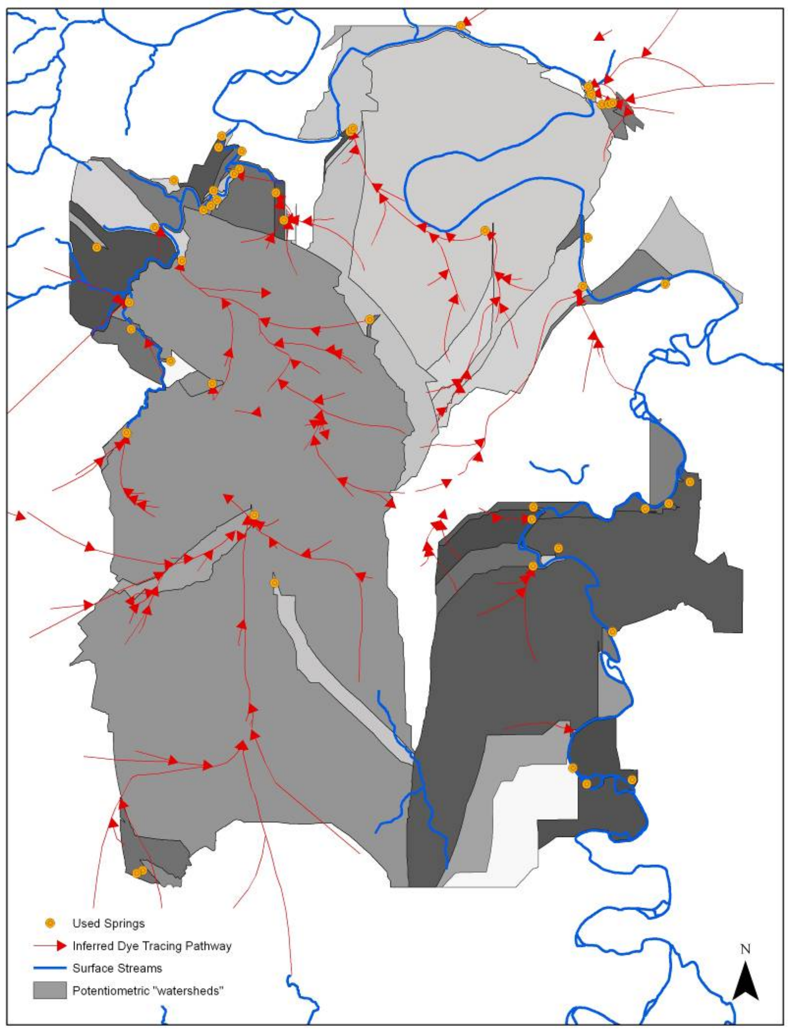


Figure 3.21 An Example of Predicted Subsurface Basins Based on Surface Springs

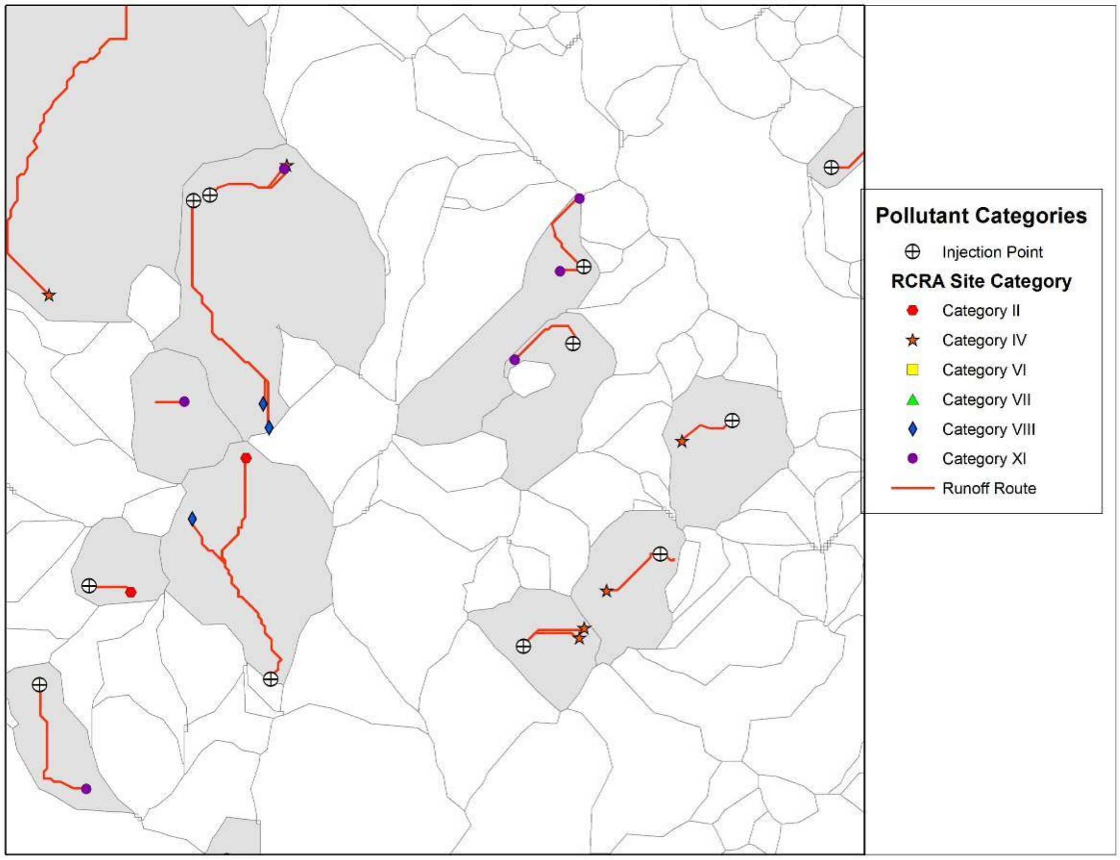


Figure 3.22 RCRA Sites and Surface Runoff Pathways

CHAPTER 4 RESULTS AND DISCUSSION

To illustrate our approach in more detail, findings from the case study conducted on Bowling Green, Kentucky are reported in this chapter. The discussion follows the framework of the conceptual model, with Sections 4.1, 4.2 and 4.3 discussing the findings in Surface Input, Subsurface Transport, and Output to Surface respectively. In each of these three sections, some critical issues are presented as well. Lastly, Section 4.4 summarizes the overall findings as well as their implications and significance.

4.1 Surface Input

The analysis in Surface Input component depicted processes in which stormwater gathers in sinksheds, transports pollutants from RCRA sites downhill and then plunges into subsurface at a nearest downhill injection point(s). The table in Appendix A includes a list of all RCRA sites in the study area and their corresponding injection points where pollutants would runoff to during a storm event. During the analysis GPS was used in the field to verify and corroborate some sinksheds and their lowest points. The network analysis task was able to create surface runoff pathways in those sinksheds with one or more RCRA sites inside. A few anomalies indeed occurred during the analysis and were corrected to create cohesive surface runoff pathways.

4.1.1. GPS Field Verification of Sinksheds

The resulted sinksheds appear to reflect accurately the characteristics of karst landscape observed in the study area, as do the sinkshed lowest points even though multiple sinkshed lowest points were usually generated. This is expected as in low sinkhole plains there could easily be a low "*field*", that is, a set of lowest points, rather than just one single lowest point. To verify this, a Trimble GeoXH GPS unit was loaded with sinksheds and their lowest points as well as streets. Point data were collected using ESRI ArcPad® 7 and Trimble® GPScorrect™ extension software. Almost all the sinksheds with multiple lowest points selected for field verification were in fact drainage basins or low flat flood plains area that are often used – at least in part – for accumulating stormwater and holding it in place while it percolates through the soil to fissures in the limestone geology below. Figure 4.1 depicts a sinkshed with multiple lowest points, located off Dishman Lane on Griffin Drive. The top figure is the GIS rendering of the features in this site while the bottom one is a photo of this retention drainage basin.

About 15% of the sinksheds generated in the study area were visited and GPS coordinates were collected at the point in each sinkshed that appears to be the lowest from an on-the-ground perspective. There is no obvious correlation as to the placement of the on-the-ground lowest point to any particular part of the collection of GIS-created lowest points within the sinkshed. Therefore, all of the sinkshed lowest points were treated as "*facilities*" in later network analysis in which the closest downhill lowest point in each sinkshed along the surface runoff pathway should be established as the terminus of runoff thus the injection point as long as there were no downhill drywells or any other physical features.

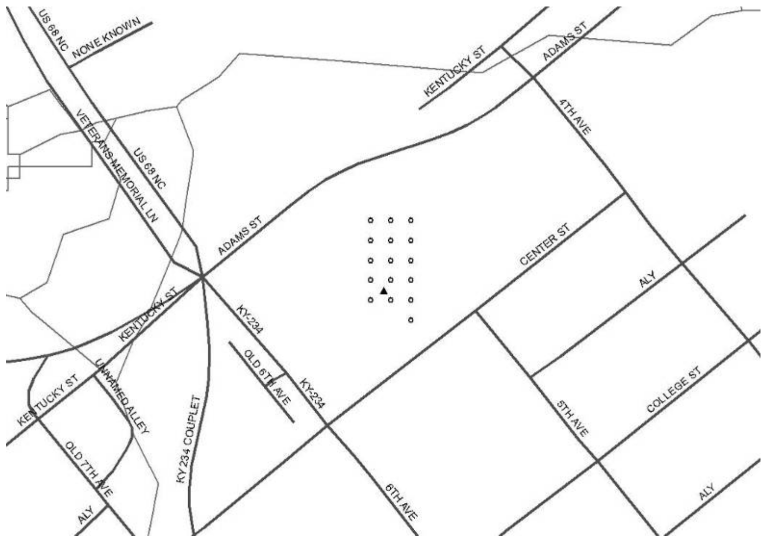
a) GIS Rendering of a Selected Sinkshed

b) Photo of the Same Sinkshed. *Photo by author.*

Figure 4.1 An Example Sinkshed and Its Drainage Basin

A very interesting observation during field verification is that some of the sinksheds actually contain stormwater injection infrastructures that are not included at all in our data inventory used for the analysis. Figure 4.2 shows the sinkshed lowest points created for a place adjacent to the skate park on Center Street (Figure 4.2a). During our visit, we observed that the site actually contained a water drainage feature that had not been inventoried in our data (Figure 4.2b). This highlights the importance of data updating and maintenance.

a) GIS Rendering of a Selected Sinkshed



b) Photo of the Same Sinkshed. *Photo by author*

Figure 4.2 An Example Sinkshed with Recently-Constructed Drainage Features

4.1.2. Two Critical Issues in Network Analysis

There are two issues that one must pay extra attention to when conducting network analysis to identify the closest downhill injection point from a RCRA site. The stream order vectors created by the hydrological tools may not all terminate at the same lowest point in a sinkshed (Figure 4.3). This is expected since in some cases stormwater would be less likely to gather at one single location rather at a low flat plain as shown in Figure 4.1. Figure 4.3 also shows a RCRA site (light blue square) with no injection point identified. To handle this issue, we basically assume that the injection point could be any of the lowest point of the sinkshed in which this RCRA site is located.

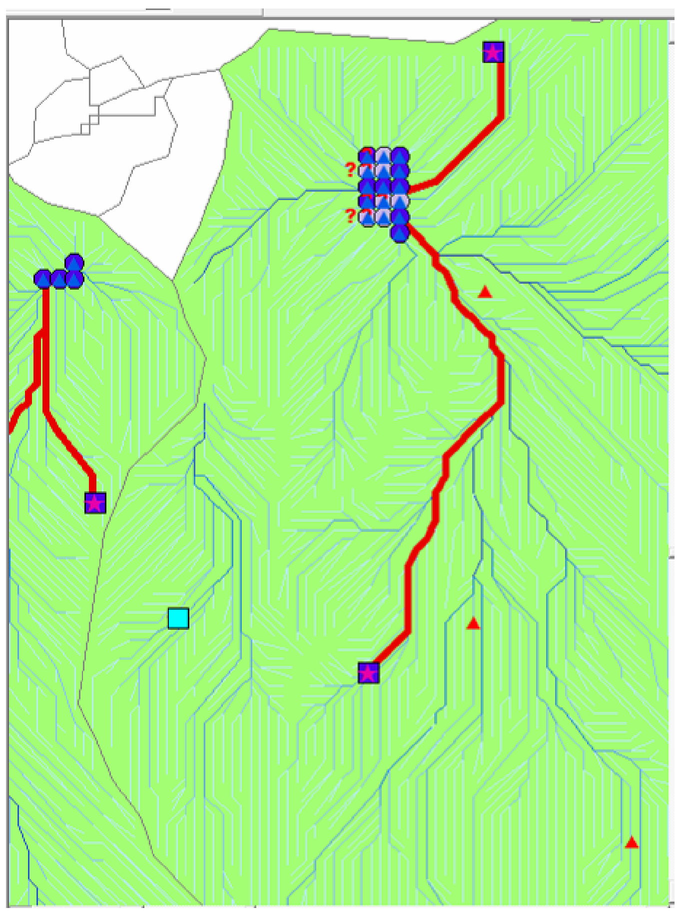


Figure 4.3 An Example RCRA Site with No Injection Point Identified

When generating surface runoff pathways, a challenge is to enforce downhill runoff. This was initially solved by setting "To-From" impedance (uphill) a very high value, and "From-To" impedance (downhill) the actual length of each streamline. This works fine in the situation when the injection point is the lowest point in a sinkshed. However when the injection points are physical features such as drywells or karst windows, not all of them were picked out with this approach. This is counter-intuitive in the real world when it is more likely that stormwater would enter the subsurface right away when running into a downhill drywell rather than settle to the sinkshed lowest points. This is because some drywells and karst windows may not be located exactly along the inferred streamlines. To solve this problem, we tested a few little higher snapping tolerances. As a result, some uphill physical features were identified as injection point as shown in Figure 4.4. When applied to other karst communities, one must choose an appropriate snapping tolerance so that an uphill physical feature will not be selected too far away from the streamlines.

4.2. Subsurface Transport

An important task in Subsurface Transport is to create a potentiometric surface, basically a raster representing the groundwater level (American Heritage Dictionary, 2009). This potentiometric surface is then used to estimate subsurface conduit pathways as well as subsurface watershed basins that feed output sites such as surface springs. The challenge is thus the selection of an appropriate spatial interpolation (SP) method that fits the basic characteristics of karst hydrogeology in the study area. Fortunately, the inferred dye tracing pathways were obtained from the Center for Cave and Karst Studies (CCKS) of Western Kentucky University (WKU) and were used to assess the accuracy of the predicted subsurface conduit pathways by a variety of SI methods. A large amount of trials and errors were involved before determining the best procedure. The following two subsections discuss these two crucial tasks of the creation of potentiometric surface respectively, the selection of control points and the choice of interpolation techniques.

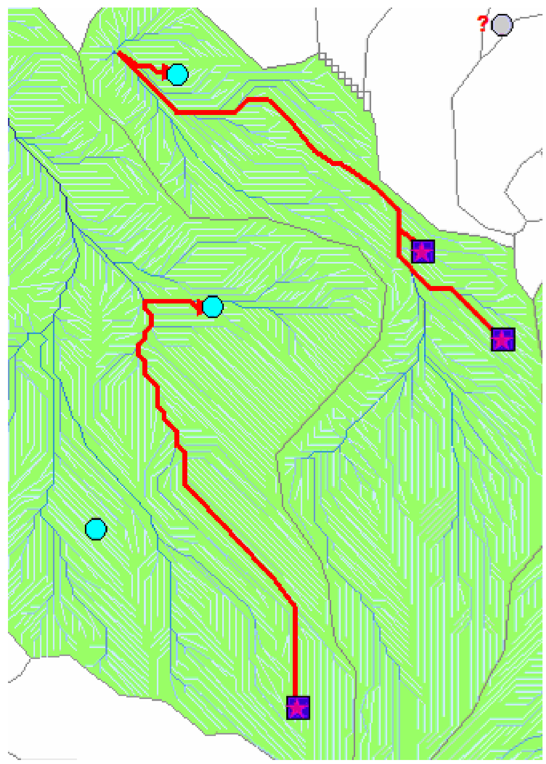


Figure 4.4 Examples of Uphill Injection Points

4.2.1. Selecting Control Points for Spatial Interpolation

Chang (2008) defines known points used in SI as “control points” or points where actual recorded sample data has been collected. The control points are then used to create an estimate or prediction of a surface that models the trends presented by those known values. The control points for creating a potentiometric surface in study area mainly include a set of point features with groundwater elevations. The main dataset is composed of 264 drywells (Figure 4.5). To increase the size of control points, we also supplemented drywells with the elevations – extracted from the DEM data – at the locations of surface springs. These points were added in that springs are usually the locations where groundwater re-merges at surface and their surface elevations usually match the groundwater elevations at the same locations.

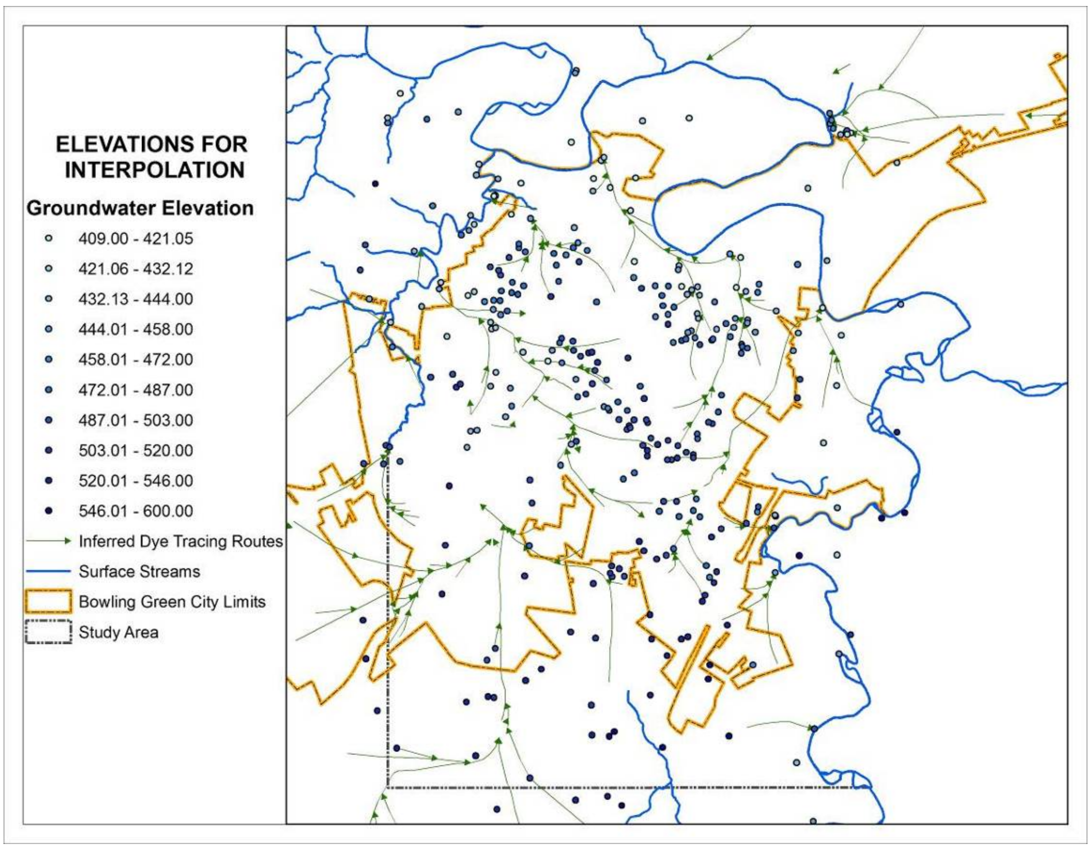


Figure 4.5 Drywells Used to Create Potentiometric Surface

In addition, the elevations of surface streams, basically the ultimate destinations of all stormwater runoff, were used as additional groundwater level information as well to improve the estimation of potentiometric surface (Figure 3.16). This process of "*burning* *in*” the surface streams to potentiometric surface essentially forced stormwater to flow into the surface streams (see Section 3.3.1 for detailed discussion on the implementation of this “burn in” procedure). This is the case in Bowling Green, Kentucky because the groundwater level in the study area happens to match the surface stream elevations. This is not always true in all karst systems – some may have underground conduits further below surface water systems, which would make the “*burning in*” technique not applicable in these terrains.

4.2.2. The Choice of Spatial Interpolation Techniques

Many mainstream GIS software, such as ArcGIS 9.3, offer a variety of SI methods. In fact, ArcGIS includes two SI toolsets, the Spatial Analyst Toolset and the Geostatistical Analyst Toolset. For this study, the tools in the Geostatistical Analyst Toolset were used because they offer more flexibility in setting up parameters for calibrating interpolation process. The principle of any SI techniques is that the value at any location can be estimated based on the known values in its proximity. As a result, the predicted values would be influenced more by closer know values than those further away (Chang, 2008). The interpolation methods tested in this study include inverse distance weighted (IDW), Ordinary Kriging, local polynomial interpolation (LPI), and global polynomial interpolation (GPI).

The result surface by IDW (Figure 4.6) is not useful in this study due to its inherent limitations. IDW, a member of the deterministic interpolation family, is based solely on a certain predetermined distance decay function. It suffers the infamous problems of “*bull’s eye*” problem as shown in Figure 4.6. When laid on top of the inferred dye tracing pathways, even though the general trend of the surface match the stippling effect of IDW, the abovementioned shortcomings make it a less-than-ideal approach for creating a potentiometric surface.

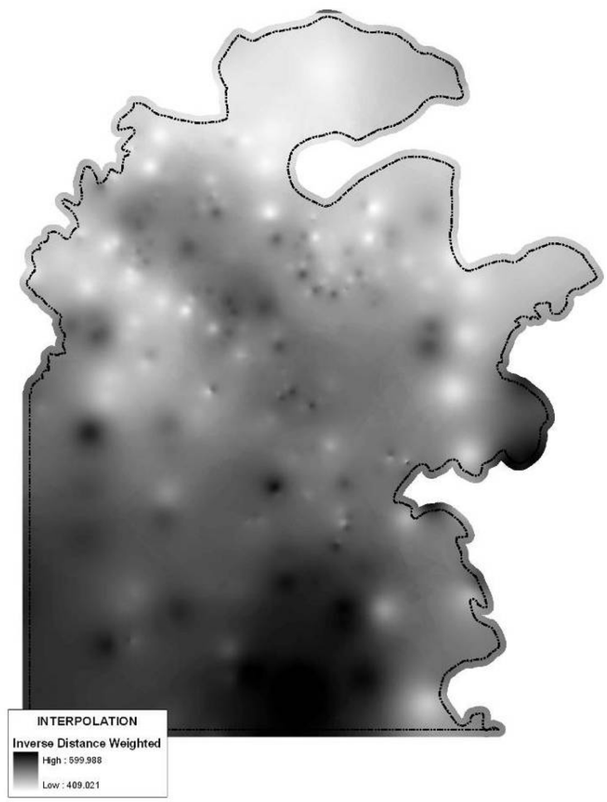


Figure 4.6 Potentiometric Surface by IDW

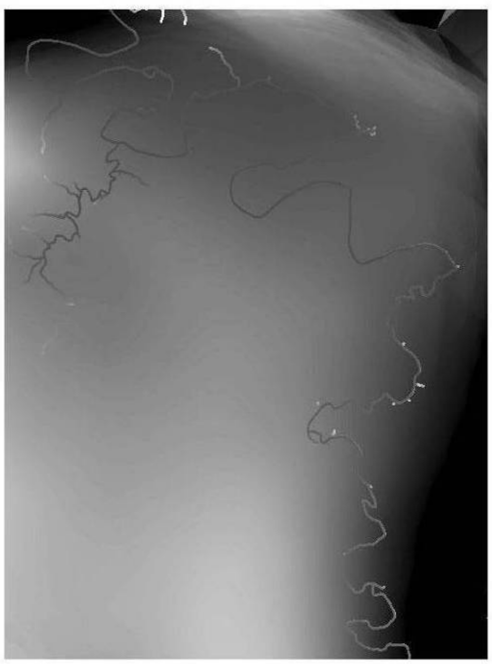
Ordinary Kriging produced a more continuous surface (Figure 4.7). As a member of stochastic interpolation family, Ordinary Kriging also takes into account the values of surrounding known points, similar to IDW. However, spatial association is not predetermined any more but derived from known values based on their statistical correlations. When compared with the inferred dye tracing pathways, a potentiometric surface estimated by Ordinary Kriging is better than that of IDW.

Figure 4.7 Potentiometric Surface by Ordinary Kriging

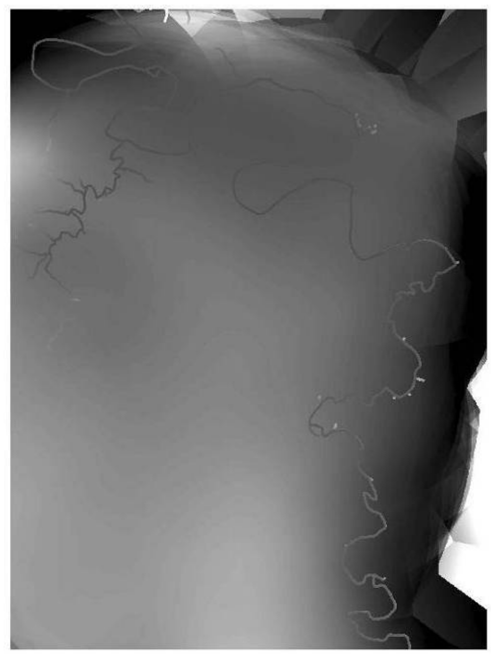
Both GPI and LPI also belong to the stochastic interpolation family. GPI uses all known values to estimate a mathematical function, often polynomial, for describing the surface, while LPI uses just a specified number of known values in the neighborhood of unknown locations. Hence an important parameter of both GPI and LPI is the power of the polynomial function and it measures the amount of bend allowed in the predicted surface. In our trials, the polynomial second-order polynomial (aka quadratic) produced the best fit when compared with the inferred dye tracing pathways. In addition, the LPI in ArcGIS Geostatistical Analyst implements an interactive dialog window via which a user can readily assign the relative importance of global (universal trend) and local effects (neighborhood property). This reflects the basic hydrogeological characteristics of a potentiometric surface in karst regions, which is largely impacted by groundwater level (represents the universal trend and often exhibits the shape of power 2 convex) and rock fractures (local effects). In the case study, a number of combinations were tested against the inferred dye tracing pathways and the combination of 80% local effects and 20% global effects resulted in the best surface to match the inferred dye tracing pathways, as shown in Figure 4.8. Figure 4.9 includes the predicted subsurface conduit pathways based on those three potentiometric surfaces in Figure 8. The differences may seem subtle, but the confluences along the groundwater surface match more closely to the potentiometric surface with 80% local effects than the other two.

Consequentially the potentiometric surface and the predicted subsurface conduit pathways can be used to determine subsurface basins that potentially feed each output spring in the study area. Figures 4.10, 4.11 and 4.12 depict the subsurface basins with varying "*snap*" tolerances. The "*snap*" tolerance refers to the distance a discharge point (in this case a surface spring) can be considered as being connected to the close by conduit pathways. For each raster, that is, the potentiometric surfaces with 60%, 70%, and 80% local effects respectively, three "*snap*" tolerances were used, including 120 feet, 360 feet, and 720 feet. A relativly large "*snap*" tolerance, such as 720 feet, should be acceptable in practice since a predicted potentiometric surface itself is estimation as well, and there would be some inevitable margin of error. But with only limited knowledge on underground karst features, choosing a relatively large "*snap*" tolerance basically ensures that surface springs can be connected to the predicted subsurface conduit pathways.

a)



b)



c)

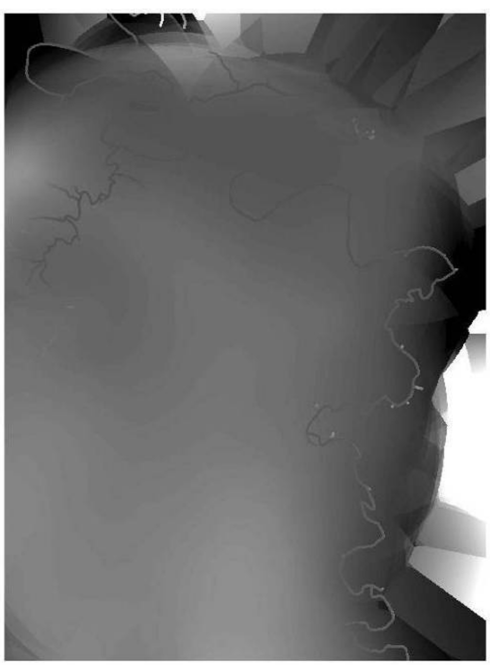
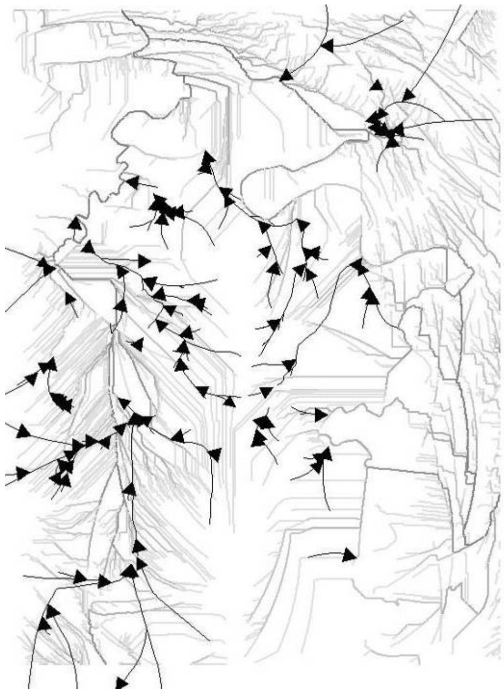


Figure 4.8 Potentiometric Surfaces by LPI. a) 60% local – second order; b) 70% local – second order; c) 80% local – second order.

a)



b)

c)

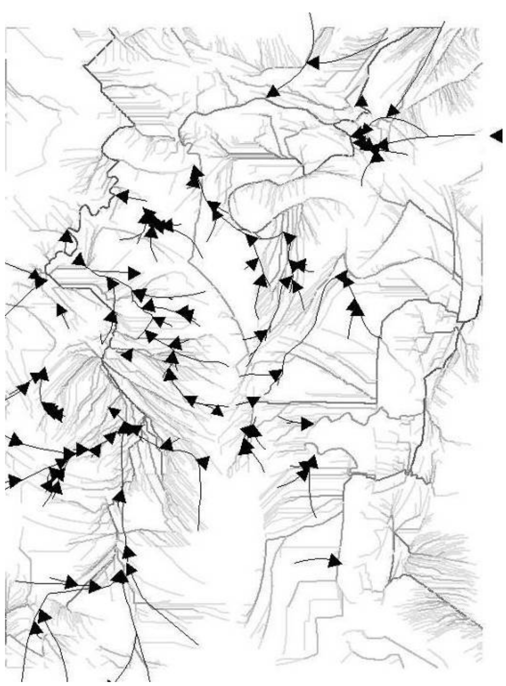
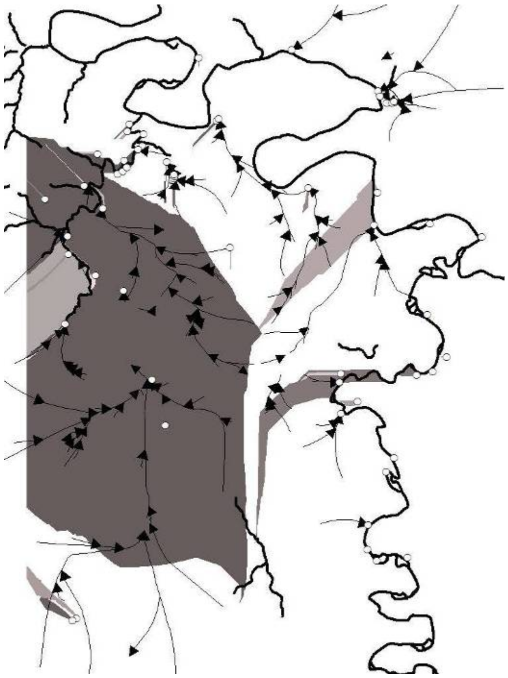
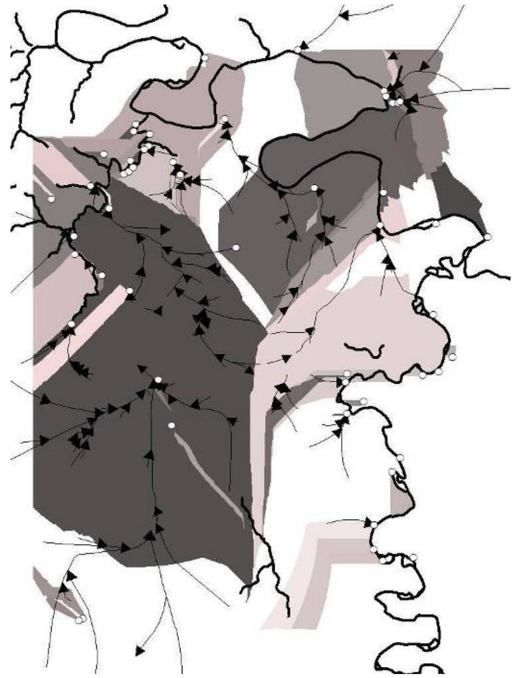


Figure 4.9 Predicted Subsurface Conduit Pathways Compared with the Inferred Dye Tracing Pathways. a) 60% local – second order; b) 70% local – second order; c) 80% local – second order.

a)



b)



c)

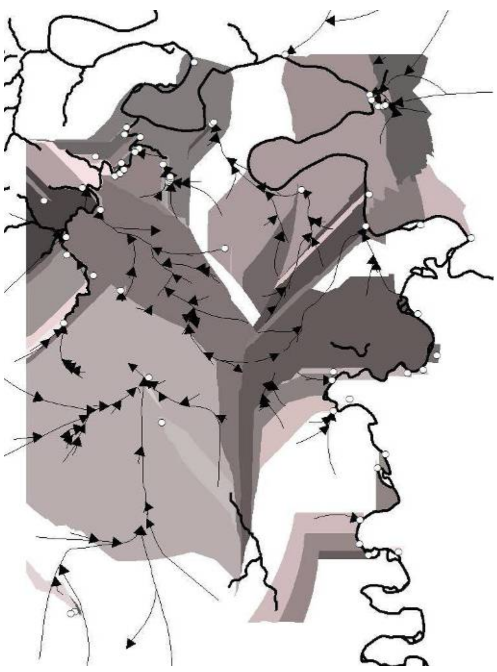
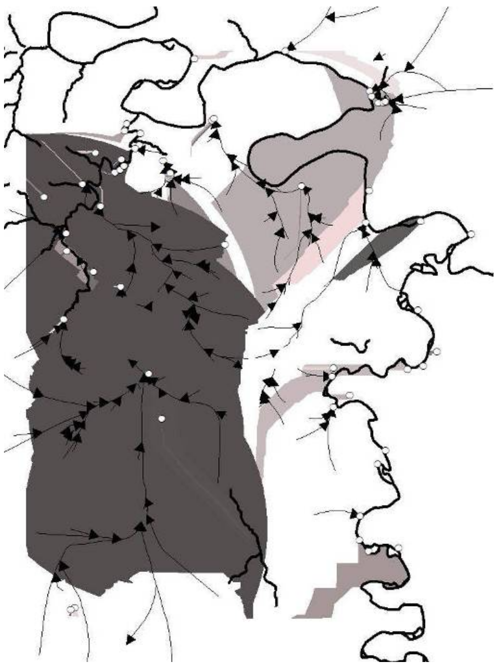
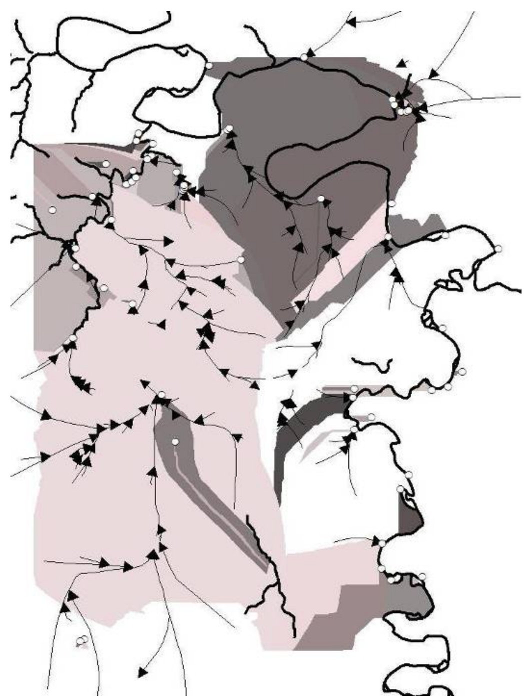


Figure 4.10 Watershed Basins Based on LPI Potentiometric Surface (60% Local). a) 60% Local – second order – 120 feet snap tolerance; b) 60% Local – second order – 360 feet snap tolerance; c) 60% Local – second order – 720 feet snap tolerance.

a)



b)



c)

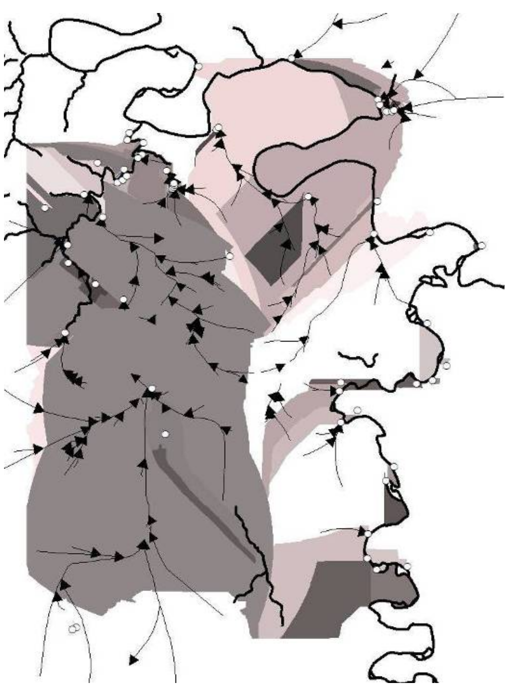
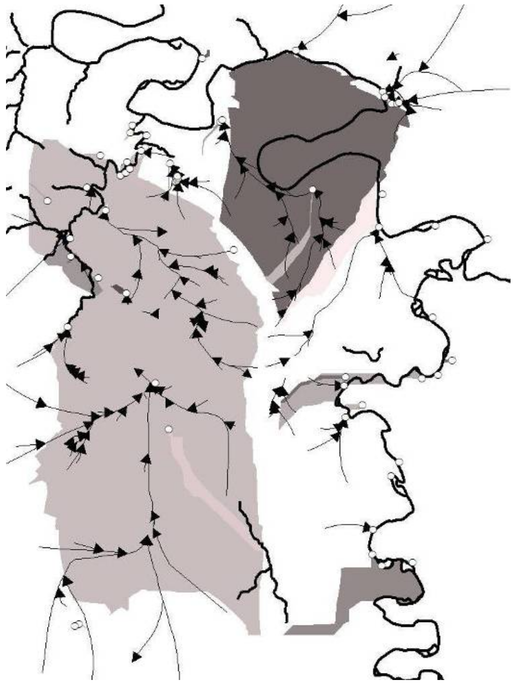
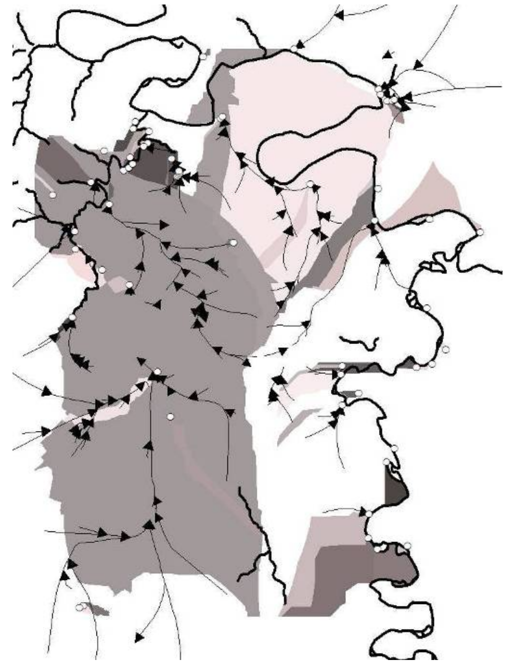


Figure 4.11 Watershed Basins Based on LPI Potentiometric Surface (70% Local). a) 70% Local – second order – 120 feet snap tolerance; b) 70% Local – second order – 360 feet snap tolerance; c) 70% Local – second order – 720 feet snap tolerance.

a)



b)



c)

Figure 4.12 Watershed Basins Based on LPI Potentiometric Surface (80% Local). a) 80% Local – second order – 120 feet snap tolerance; b) 80% Local – second order – 360 feet snap tolerance; c) 80% Local – second order – 720 feet snap tolerance.

4.3. Output to Surface

In the conceptual model, stormwater would ultimately exit subsurface and discharges back to surface streams at surface springs. In order to identify the connections among injection points and output springs, the predicted subsurface watershed basins (Figure 4.13, 80% Local – second order – 720 feet snap tolerance) were overlaid with injection points, as shown in Figure 4.14, and surface springs, as shown in Figure 4.15. Basin 99, the largest potentiometric basin, runs along the west side of the study area and accumulates the stormwater runoff from the most number of injection points in the study area - 27 injection points. It is expected that its corresponding output spring draw the most possible sources of RCRA runoff. Indeed this basin accurately matches the inferred dye tracing pathways. Sampling at this location would result in the most variety of potential RCRA runoff contaminants as well as stormwater pollutants from other sources such as farmlands or construction sites. Notice that in Figure 4.14 not all parts of the study area are covered with the predicted subsurface watershed basins, particularly on the eastern side of the study area near the confluence of the Barren River and Drake's Creek. This area, where 11 injection points are located, is not associated with any spring as viable output. We suspect that there would be some discharge points that are not included in the current spring dataset that we used. Likewise, the predicted subsurface watershed basins were also overlaid with surface springs (Figure 4.15). Any springs covered by a subsurface watershed can be treated as viable sampling sites for monitoring the transport of stormwater pollutants. As a matter of fact, any injection point and any spring covered by a same subsurface watershed polygon can be considered linked, with injection points as input and surface springs as output of the groundwater system. In the end, we were to establish the connections among RCRA sites and output surface springs based on the connections we concluded among RCRA sites and injection points in the analysis of Surface Input (See Appendix A).

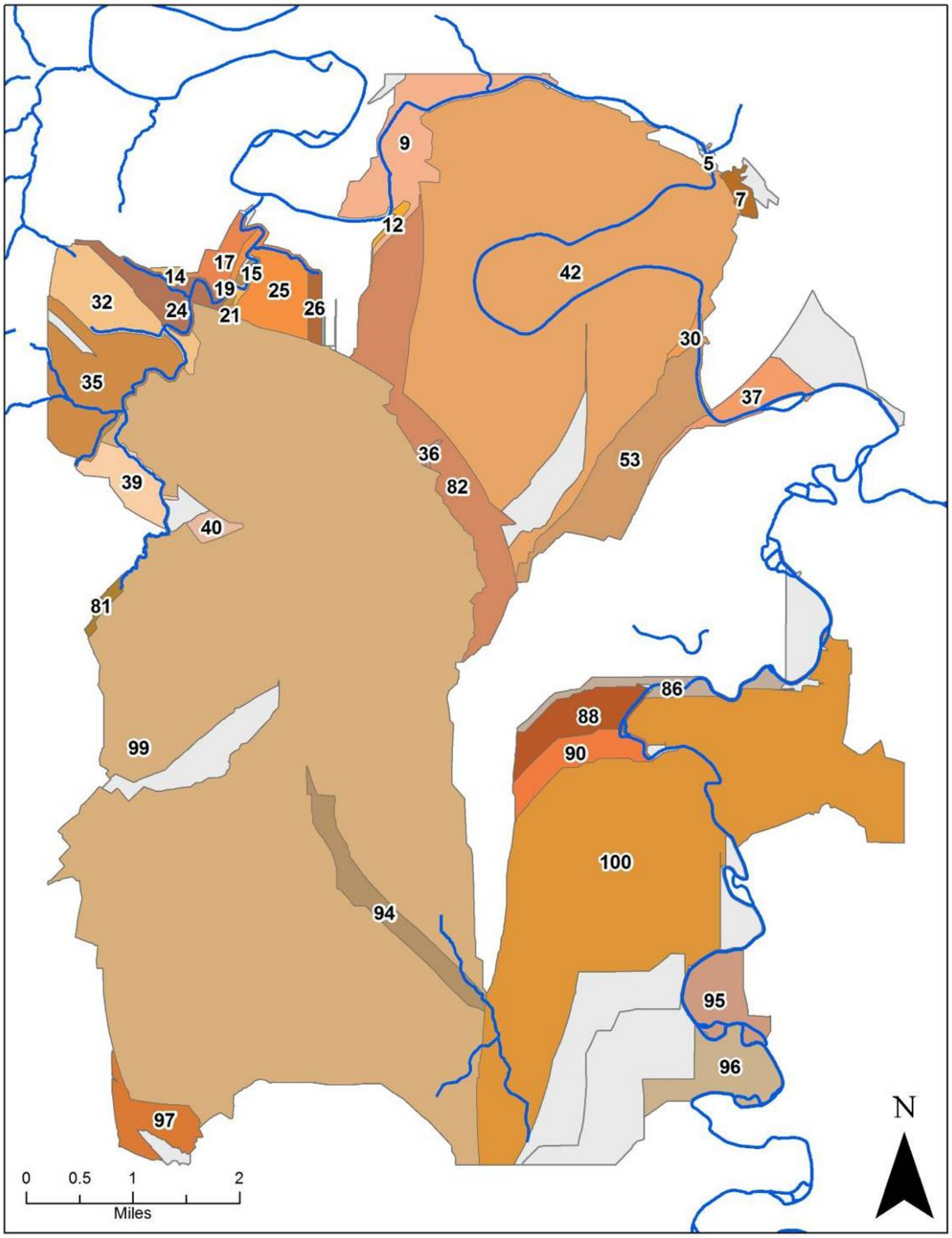


Figure 4.13 The Predicted Subsurface Watershed Basins

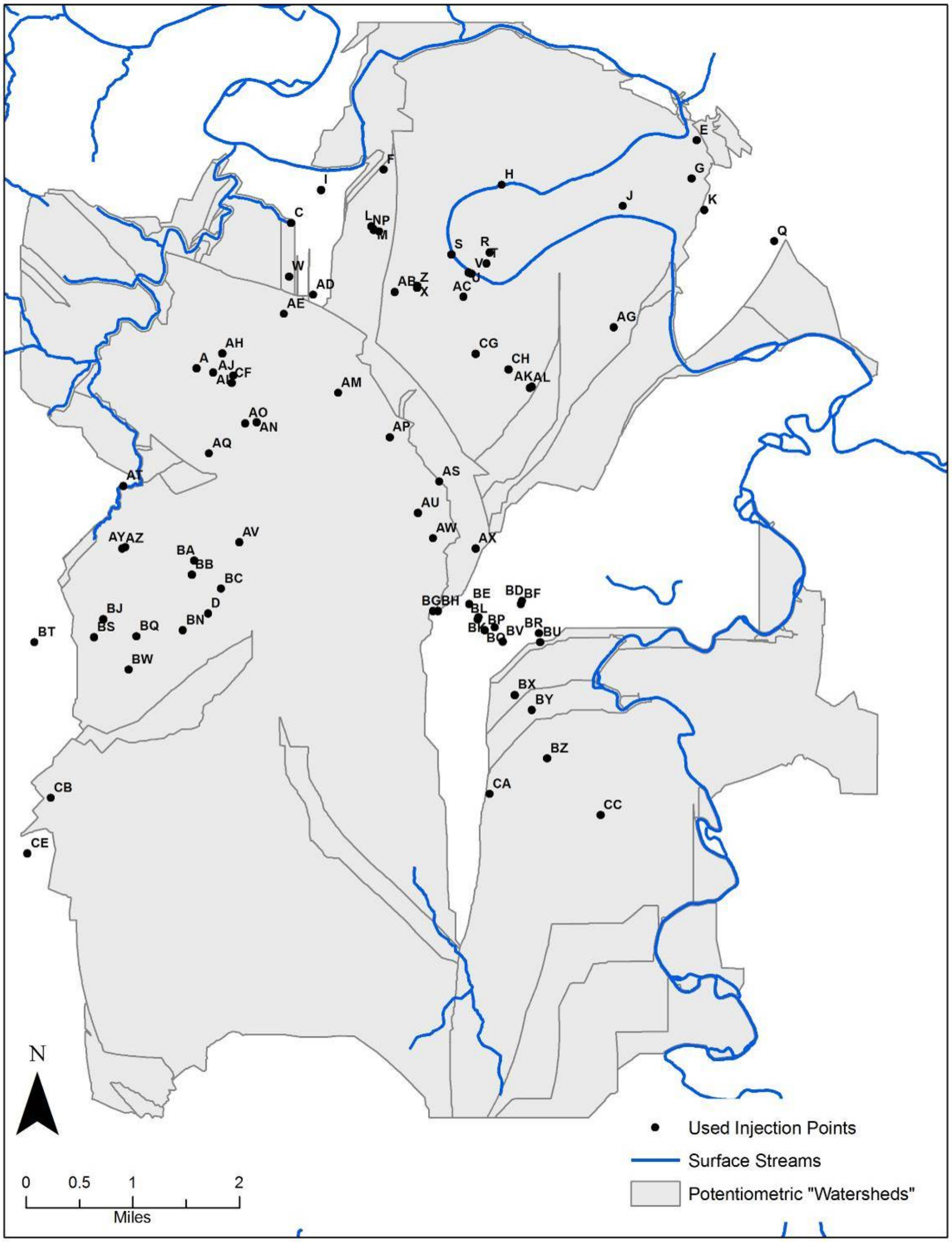


Figure 4.14 Injection Points Overlaid on Subsurface Watersheds

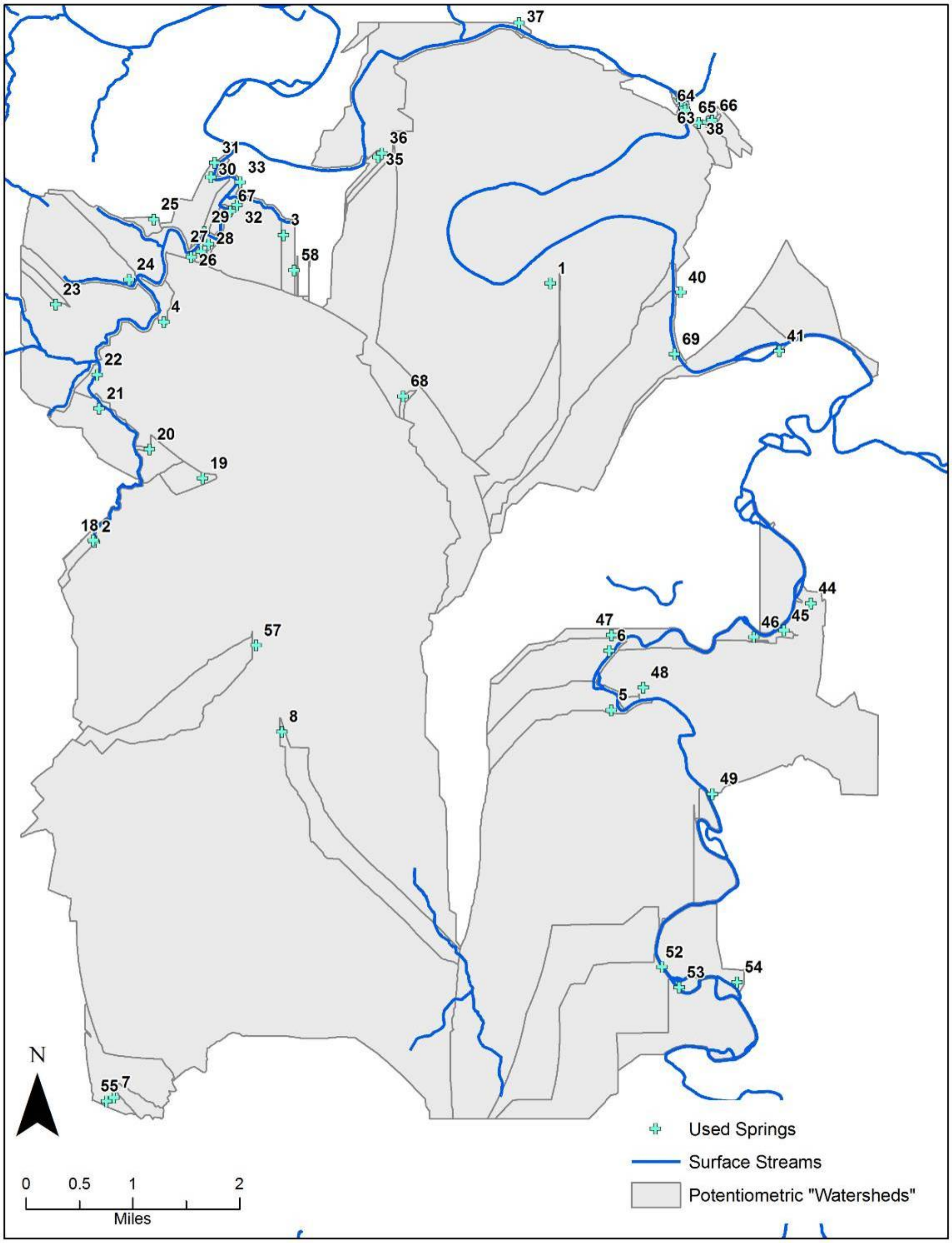


Figure 4.15 Surface Springs Overlaid on Subsurface Watersheds

4.4. Overall Results, Implications, and Significance

Each of the three components of the conceptual model yielded its own results as discussed in previous three sections. The significance of the results, however, lies in the cumulative outcomes of the whole analysis process. The results from the case study demonstrate the ability of the approach in predicting surface runoff pathways and subsurface conduit pathways in karst regions. The predicted subsurface runoff pathways and subsurface basins reflect the basic tendencies and flow directions of the inferred dye-tracing pathways, especially on the west side of the study area. Figure 4.16 depicts the potentiometric watersheds created by the hydrological analysis as well as the inferred dye tracing pathways. As discussed before in Section 4.3, in order to identify the connections among injection points and output springs, the injection points and surface springs can both be overlaid on top of the potentiometric watersheds as shown in Figure 4.16, where stormwater feed into their respective watersheds at injection points and discharge back to the surface streams at the output springs. Not all the injection points are associated with a subsurface basin mainly because there were no corresponding output springs identified in the spring dataset.

The injection points and springs associated with each subsurface watershed basin are shown in Figure 4.16. The springs were obtained from Bowling Green Warren County Planning Commission. Most springs sit in close proximity to Barren River, Drakes Creek, or Jennings Creek. These springs are where the runoff re-enters the surface system and feeds into the surface streams. The subsurface watershed boundaries outline the basins that collect groundwater for output at springs. Surface springs are important in this study as they are viable sites to collect stormwater samples and to determine collaborative strategies for monitor stormwater runoff. The table in the Appendix A lists the detailed outcomes of the case study for all RCRA sites, including the ID of each RCRA site, the type of industry or contaminant that may be associated with polluted stormwater runoff at each RCRA site, the ID of the injection point at which each RCRA runoff flows into, the ID of the subsurface basin that collects stormwater from each RCRA site, and most importantly the ID of the output spring linked to each RCRA site.

In summary, the findings of the case study suggest that GIS can be used to roughly predict potentiometric surface and output springs where stormwater can be monitored and sampled. Even though some areas of uncertainty were yielded in the analysis, the results matched what would be expected based on the inferred dye-tracing pathways, especially in the west portion of the study area. Of course, it would be nice to have more input data (*e.g.* well depths) for estimating potentiometric surface and more up-to-date dataset to generate more accurate runoff pathways on both surface and subsurface, even though for this particular study it is not needed at all to produce the precise subsurface runoff pathways between the injection points and their corresponding spring as the pathways themselves are not as important in this study as determining the connections among RCRA sites and surface springs. Overall, this study lays the groundwork for further investigations in determining runoff pathways in karst regions. It also has implications into other areas of karst water management, such as dye tracing and groundwater sensitivity studies.

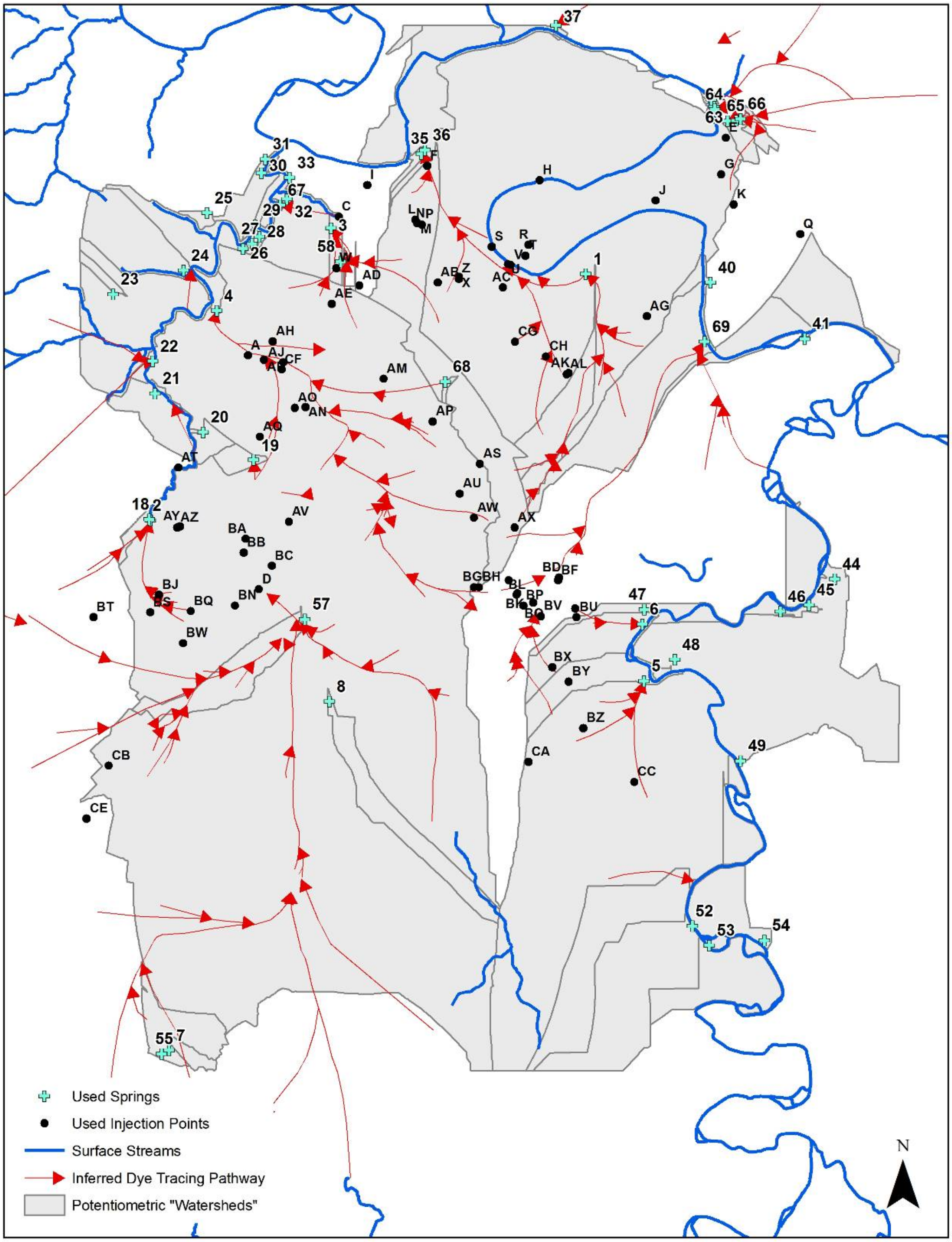


Figure 4.16 Potentiometric Watersheds Overlaid with Injection Points and Springs

Dye tracing procedures take time, careful planning, and field reconnaissance before beginning the actual dye tracing implementation. Our approach can aid the preparation for dye traces. One example would be the sinkshed and identification of lowest points of sinksheds. In karst regions, often the presence of sinkshed lowest points indicates the existence of a karst feature or karst window. Over time, the accumulation of water in these lowest points erodes the limestone geology, creating direct conduits form the surface to the subsurface. Identification of sinksheds and their lowest points with GIS can direct analysts to the areas of interest in the field and thus minimize time that might be spent exploring unfamiliar areas. In addition, the prediction of subsurface conduit pathways can also be beneficial for the anticipation of dye tracing pathways.

Another area that our approach can be useful is groundwater sensitivity study. Being able to determine stormwater runoff injection points in karst regions is of great importance because the runoff is injected directly into karst subsurface and can travel - without any filtration or treatment – to drinking water sources or other locations that may contribute to the degradation of public health. Several models have been created to categorize the environment into levels of groundwater sensitivity based on how vulnerable it is to contamination from runoff. Croskery's study (2005) assessed the Barren River Development District (a 10-county area including Warren County, in Southwestern Kentucky) for groundwater sensitivity. All the injection points in this study fell into the High Sensitivity category indentified by Croskery (Figure 4.17). Knowing the placement of injection points and the level of sensitivity in the area allows for government officials to mandate stricter monitoring and enforcement procedures for

RCRA sites and other sites that are prone to runoff. This can work towards minimizing the concentration of contaminants that reach these critical karst groundwater resources.

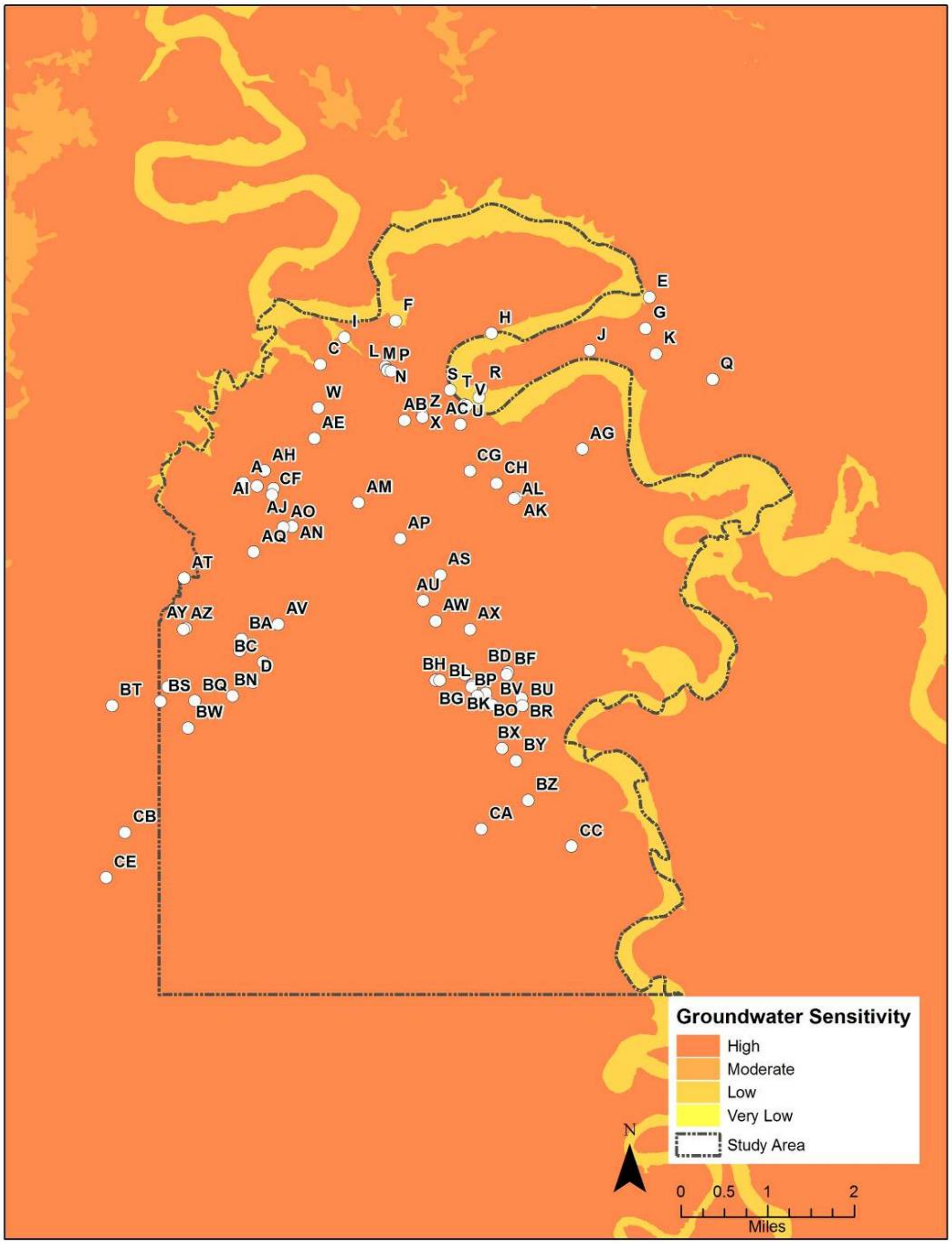


Figure 4.17 Injection Points Overlaid on Groundwater Sensitivity Designations for the Barren River Development District (BRADD). *Source: adapted from Croskrey, 2005.*

CHAPTER 5 CONCLUSIONS AND FUTURE RESEARCH

5.1. Conclusions

This study describes conceptually three stages of stormwater pollutant transport in karst regions: the surface runoff, the subsurface transport, and output to the surface. The Surface Input is used to predict the stormwater runoff processes occurring between the RCRA site and the injection point. In particular, sinksheds and their lowest points were identified and some were verified for accuracy by GPS assessment in the field. The results of Subsurface Transport included potentiometric watersheds depicting basins where stormwater in subsurface collects and ultimately discharges back to surface streams at some output springs. The predicted potentiometric watersheds match the patterns from the inferred dye tracing pathways, especially in the west side of the study area. The analysis done in Output to Surface was able to identify the connections from RCRA sites to injection points and from injection points to surface springs (see Appendix A). The pathway from each RCRA site to its corresponding output springs was identified consequentially and verified by the inferred dye tracing pathways.

A few lessons were learned in the case study. The field verification with GPS coordinates ensured the accuracy of sinksheds and their lowest point. Also, it is crucial to choose the "*right*" spatial interpolation technique for predicting potentiometric surface – not just that makes sense in theory – but a technique that accurately portrays patterns in the input data. We also learned that potentiometric surface could be enhanced by adding other data sources of groundwater table. Lastly, this thesis research highlights the importance of a complete and up-to-date inventory of data. For instance, having more current data for injection and spring features in the study area would surely improve the results.

While the best way to assess runoff patterns through karst subsurface is through detailed and methodical dye tracing and cave surveying and map procedures, many communities may not have the resources - both financial and academic – to perform the costly procedures involved to procure these results. The methodology described in this study would provide an educated idea of the conduit trends in similar karst environments at a significantly lower cost than dye tracing procedures. Implementation of the techniques described in the study with the correct and thorough spatial datasets necessary to complete the analyses can supplement dye tracing data for a community in the creation of runoff maps and monitoring plans that can help manage water quality and environmental health in compliance with federal and local guidelines.

5.2. Future Directions

The methodology developed in this research lays a foundation for further investigations in several fields. There are several tangents and verifications of this study that would help refine techniques adopted in this study. Further studies can be implemented to create a more informed water sampling plan. The approach could also be expanded to non-point source runoff from agricultural fields or residential communities.

5.2.1. Water Quality Sampling Plan

The primary goal of this study is to determine the input and output locations of stormwater runoff from known sources to best determine stormwater pollutant transport pathways through karst features. Naturally the next step is to develop a stormwater monitoring plan to collect and process water samples from springs. The numerous constraints to creating a balanced and through water quality monitoring plan are largely spatial in nature and would lend itself well to the use of GIS technologies. One consideration would be the transportation aspect of water quality sampling: which sampling sites are in close proximity to which roadways, how many sites can be sampled and returned to the lab for processing within the parameters of the pollutants being viable for analysis, or what is the travel time to a sampling site to be able to sample the runoff that is a product of a storm event could all be answered using GIS as part of the analysis.

Another consideration is the type of potential runoff that is entering the stormwater system. The EPA has several categories of types of pollutants such as byproducts of light manufacturing in one class, metal and auto salvage yards in another, coal and mineral mining sites in a third class, etc. Stormwater runoff sampling guidelines require not only a certain percentage of sites to be sampled annually, but also an array of contaminant types be sampled as well in order for stormwater managers to be fully aware of the range of runoff occurrences in their jurisdiction. GIS can be used to examine the distribution of different categories of pollutant runoff and determine the most efficient way to sample in order be cost and time efficient, as well as compliant with all sampling guidelines.

5.2.2. Water Quality Sampling

After a water quality sampling plan is created, the next step in the process would be to test both the reliability of the transport model as well as the efficiency of the of the stormwater runoff sampling plan. This is a crucial step in refining any further methodologies. The GIS analysis used to create the input and output locations could be verified by further dye tracing, or sampling for output at locations where known inputs could be confirmed. In addition to water sampling, field data collection of more drywell depths to water table, spring locations, and new well features can be added in the GIS database to update the analysis.

5.2.3. Modeling Non-Point Source Runoff

This thesis reach mainly focuses on stormwater runoff from point source pollution, in particular, the RCRA sites. The EPA Phase II Stormwater Regulations also include non-point source pollution from a variety of land use types. One option would be to take the USGS Land Use and Land Cover Classification data (Anderson, et al 1976) to delineate the various land cover types in the study area (Figure 5.1). Once the land areas are designated by their land use (*i.e.* low density urban, cropland, forested area, etc.), a similar approach could be developed to determine runoff pathways, injection points and output sites for non-point source stormwater runoff. The results of a non-point source pollutant stormwater runoff study would help with the compliance of stormwater sampling. It would also enable city managers to direct education and best management practice (BMPs) efforts towards certain land use types. For example, city ordinances could change to require new parking lots to be constructed out of permeable materials if runoff from high intensity urban areas results in samples with high pollutant concentrations. They can also provide education to farmers' organizations on fertilizer applications and runoff control BMPs if croplands yielded high pollutant runoff samples.

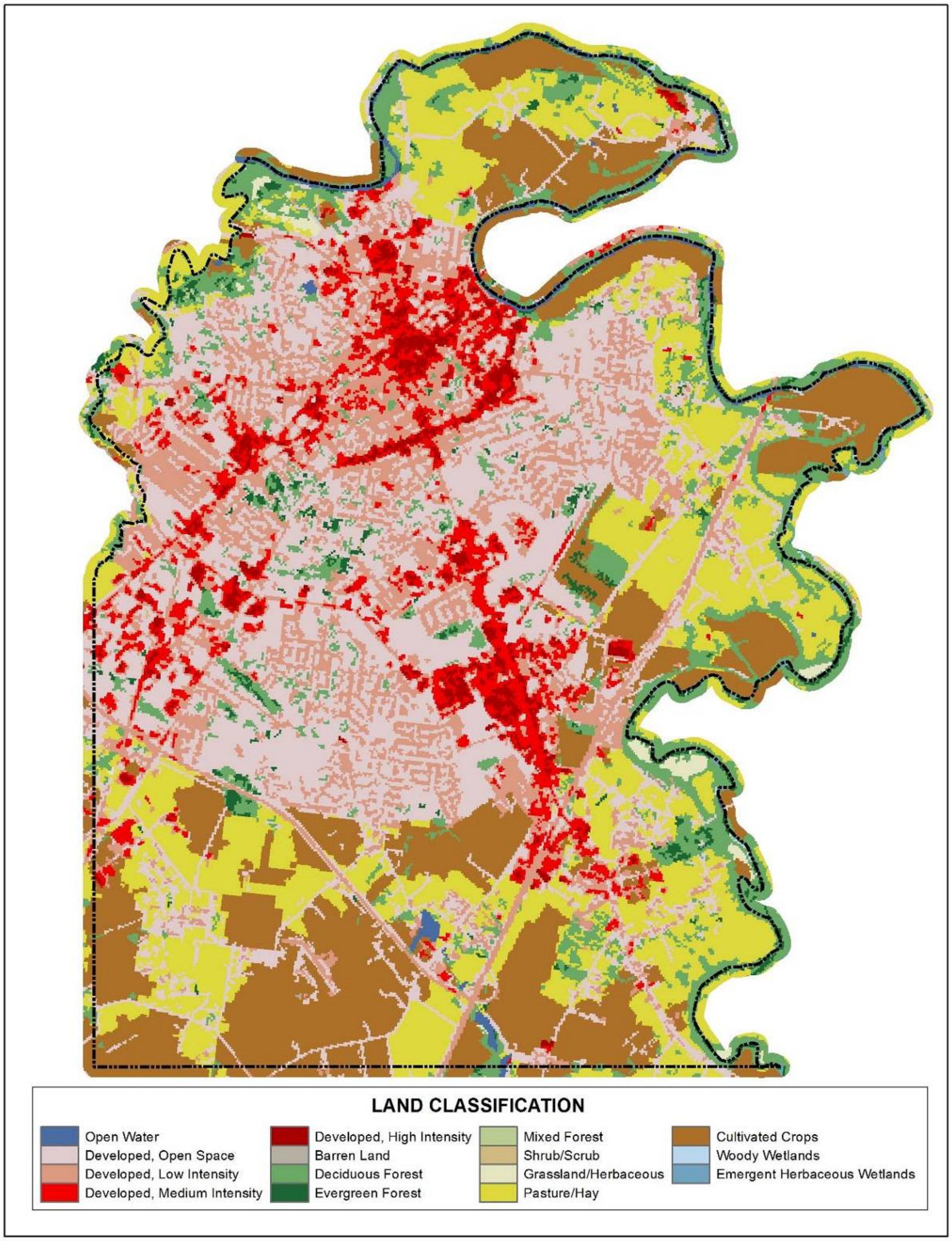


Figure 5.1 Land Use Distribution in the Study Area. *Source: map created using USGS National Land Cover Dataset, 2001.*

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APPENDIX A

RCRA Site	Type	RCRA ID	Injection ID	SubBasin ID	Spring ID
1226 US 31W Bypass	Gas	1	AP	99	22, 57
AMCOR Flexibles Inc	Plastics	3	Q	N/A	N/A
American Sunroof Co.	Manufacturing - Auto Parts	4	H	42	1
Aratex Services Inc.	Gas	5	AO	99	22, 57
Bellsouth Telecommunications	Telecommunication	6	BR	N/A	N/A
Big B Cleaners #110	Dry Cleaner	8	AB	42	1
Big B Cleaners #118	Dry Cleaner	10	CG	42	1
BG St. Vo-Tech School	Unknown	13	A	99	22, 57
Bowman Automotive	Auto Repair	14	AE	99	22, 57
Bypass Shell	Gas	15	V	42	1
C&R Towing Inc.	Unknown	16	S	42	1
C.C. Hildreth/JR. Food Store	Grocery	17	D	99	22, 57
Certified Environmental Recycling	Unknown	19	Z	42	1
Charlie’s Body Shop	Auto Repair	20	BQ	99	22, 57
Chevron Products #48715	Gas	21	CG	42	1
Chevron USA	Gas	22	AO	99	22, 57
Chevron USA Products #204290	Gas	25	BN	99	22, 57
City of Bowling Green	Unknown	26	M	82	?
Clark Store #1450 (former)	Gas	27	AD	N/A	N/A
Colt Industries Inc. Holley Replacement Parts	Manufacturing - Carburetor	28	?	99	22, 57
Country Oven Bakery	Unknown	29	BS	99	22, 57
CSX Transportation	Railroad	30	AZ	99	22, 57

RCRA Site	Type	RCRA ID	Injection ID	SubBasin ID	Spring ID
Danny Copas Excavating	Unknown	32	AM	99	22, 57
Detrex Corp	Manufacturing - Metal	33	AQ	99	22, 57
Detrex Corp. Parts Cleaning	Electroplating	34	AQ	99	22, 57
Detrex Corp. Technology Center	Wholesale - Machinery	35	AQ	99	22, 57
Eagle Industries Plant	Manufacturing - furniture	36	N	82	?
Eagle Industries Plant #2	Manufacturing - furniture	37	C	26	3, 58
Eaton Corp	Manufacturing - Relay	38	BA	99	22, 57
Federal Express Corp. BWGA	Courier	39	BU	86	45,46, 47
Firestone	Auto Store	40	AP	99	22, 57
Fuji Photo Film USA Inc	Wholesale - Photo Equipment	41	A	99	22, 57
Garrison Service Co.	Wholesale - Machinery	42	AT	N/A	N/A
Gate Station #608	Gas	43	CF	99	22, 57
Goodyear Auto Service Center	Unknown	46	AB	42	1
Greenbay Packaging Inc.	Unknown	47	I	N/A	N/A
Greenwood Sunoco	Gas	48	BZ	100	44,48,49
Hayes Lemmerz International Inc.	Manufacturing - Auto Parts	49	CE	N/A	N/A
Hennesy Industries Inc. Bada Division	Manufacturing - Metal	50	?	N/A	N/A
Hills Pet Nutrition, Inc.	Manufacturing - Pet food	51	AY	99	22, 57
Hinton Cleaners, Inc.	Dry Cleaner	52	CG	42	1
Jim Johnson Collision Center	Auto - Repair	55	CH	42	1
Ken Wallace Ford, Inc.	Unknown	56	CG	42	1
Kentucky Micro Finishing, Inc.	Electroplating	58	BB	99	22, 57

RCRA Site	Type	RCRA ID	Injection ID	SubBasin ID	Spring ID
Kerr Group, Inc.	Manufacturing - Plastics	60	CB	99	22, 57
L&N Railroad Depot	Buildings	62	X	42	1
Lord Corp	Manufacturing - Rubber	63	BJ	99	22, 57
MAACO Auto Painting & Bodyworks	Auto - Repair	64	U	42	1
Mail Well Label USA, Inc.	Printing	65	CB	99	22, 57
Medical Center at BG	Hospital	66	AC	42	1
Minit Mart #35	Gas	69	AD	N/A	N/A
Minit Mart #42	Gas	70	AI	99	22, 57
Minit Mart #56	Gas	72	BR	N/A	N/A
Minit Mart #83	Gas	73	BN	99	22, 57
News Publishing Co.	Newspaper	74	-	42	1
Nylon Craft of KY	Unknown	78	G	42	1
PB&S Chemical Co.	Manufacturing - Alkalis	79	C	26	3, 58
RC Components, Inc.	Electroplating	82	CB	99	22, 57
RAD Chemicals, Inc.	Manufacturing - Chemical	83	BW	99	22, 57
Tender Touch Express Car Wash	Car Wash	84	CG	42	1
Scott Mclean Inc.	Millwork	88	C	26	3, 58
Sherwin Williams, Co	Unknown	89	CG	42	1
Smith Gordon & Co. Inc.	Manufacturing - Air Compressor	90	T	42	1
Smith Painting Inc.	Painting	91	E	42	1
Southern KY Auto Brokers	Auto - Dealer	92	AZ	99	22, 57
Southern KY Rebuilders, Inc.	Unknown	93	AN	99	22, 57
Spirit Services, Inc.	Laundry	94	L	82	?

RCRA Site	Type	RCRA ID	Injection ID	SubBasin ID	Spring ID
Stupp Bridge Co.	Manufacturing - Metal	97	CB	99	22, 57
TVA	Electric Power	98	F	82	?
TOC Retail Inc. #602-15	Gas	100	AV	99	22, 57
Turner Industries Inc.	Fabric Mill	101	?	N/A	N/A
Turner Industries II, Ltd.	Unknown	102	C	26	3, 58
United Parcel Service	Courier	103	AY	99	22, 57
United Parcel Service_Vehicle	Unknown	104	AB	42	1
Valspar Industires, Inc.	Manufacturing - Paint	105	CB	99	22, 57
Western Kentucky University	College	107	W	26	3, 58
Western Kraft Paper Corp.	Unknown	109	Q	N/A	N/A
WKU Ogden College	College	110	AM	99	22, 57
WKU S. Campus Complex	College	111	BC	99	22, 57
Whayne Supply Co.	Construction	113	AK	42	1
Wilkinson Equipment	Petroleum Terminal	114	BD	N/A	N/A
Woodwork of MidAmerica	Manufacturing - Rubber	115	G	42	1
Yellow Freight System, Inc.	Freight - Trucking	116	K	N/A	N/A
Youngs Delux Cleaners	Dry Cleaner	117	AP	99	22, 57
Bando Manuf. Of America, Inc.	Manufacturing - Rubber	118	BQ	99	22, 57
BG Municipal Utilities	Utilities	119	AB	42	1
DESA International, Inc.	Manufacturing - Heating	120	BA	99	22, 57
Greenview Hospital	Hospital	121	AW	99	22, 57
Holley Performance Products, Inc.	Manufacturing - Machinery	122	AO	99	22, 57
Housing Authority of BG	Housing	123	P	82	?
Huntsman Film Products Corp.	Manufacturing -	124	BT	N/A	N/A

RCRA Site	Type	RCRA ID	Injection ID	SubBasin ID	Spring ID
	Paper				
James River Paper Co. Inc	Manufacturing - Container	125	CB	99	22, 57
KY National Guard – OM Shop #10	National - Security	126	AH	99	22, 57
Minit Mart #65	Gas	130	-	42	1
Shell One Stop	Gas	132	R	42	1
Speedway #8646	Gas	134	BX	88	6
TPM, Inc.	Consulting	135	R	42	1
Bellsouth Telecommunications, Inc.	Unknown	136	BF	N/A	N/A
Diamond Equipment of KY, Inc	Wholesale - Machinery	138	BV	N/A	N/A
SCA Incontinence Care	Fabric Mill	140	J	42	1
Southern Salvage & Removal	Freight - trucking	141	AG	42	1
Big B Cleaners #112	Dry Cleaner	142	BH	82	?
Campbell Chevrolet	Auto - Dealer	143	BP	N/A	N/A
Concord Custom Cleaners	Dry Cleaner	144	AS	99	22, 57
Fabric Cleaners	Unknown	145	BX	88	6
Gary Force Honda	Auto - Repair	146	BE	N/A	N/A
Gary Force Paint & Body	Auto - Repair	147	BL	N/A	N/A
Gary Force Toyota Mazda	Auto - Repair	148	BK	N/A	N/A
Greenwood Ford, Inc.	Auto - Dealer	149	BY	90	5
Jim Johnson Pontiac Nissan	Auto - Repair	150	BO	N/A	N/A
Leachman Buick GMC	Auto - Repair	151	AX	82	?
Martin Oldsmobile	Auto - Dealer	153	BO	N/A	N/A
Overland Transporation System, Inc.	Freight - Trucking	154	CA	100	44,48,49
Scotty's Speed & Custom, Inc.	Retail - Auto	155	BK	NA	NA

RCRA Site	Type	RCRA ID	Injection ID	SubBasin ID	Spring ID
Sears #2546/7396	Auto - Repair	156	BO	NA	NA
Super America #5370	Gas	158	BG	99	22,57
Tower Automotive Products Co., Inc.	Manufacturing - Auto Parts	159	CC	100	44,48,49
Warren Environmental	Freight - trucking	160	AU	99	22, 57

Table A.1. RCRA Sites and Their Corresponding Injection Point, Potentiometric Watershed & Associated Spring

APPENDIX B – DATA SOURCES

Data	**Source**
10-M Digital Elevation Model (DEM)	Kentucky Geography Network (kygeonet.ky.gov)
Potential Pollutant Sites	Resource Conservation Recovery Act
Surface Streams	National Hydrologic Dataset (USGS)
Karst Windows	Bowling Green Warren County Planning Commission
Swallets	Bowling Green Warren County Planning Commission
Springs	Bowling Green Warren County Planning Commission
Well depths	Bowling Green Warren County Planning Commission
Inferred Dye Tracing Pathways	Center for Karst and Cave Studies, Western Kentucky University

Table B.1. Data Sources

APPENDIX C – TOOL PARAMETERS

Sinkshed Creation Parameters

Tool	Parameter	Setting
Flow Direction	Input	Unfilled 30ft DEM
	Output	Flow direction raster
Flow Accumulation	Input	Flow Direction Raster
	Output	Flow Accumulation Raster
	Output Data Type	Float
Sink	Input	Flow Direction Raster
	Output	Sink Raster
Snap Pour Point	Input	Sinks raster
	Input	Accumulation Raster
	Output	Snap Pour Point Raster
	Snap Distance	0
Watershed	Input	Flow Direction Raster
	Input	Snap Pour Point raster
	Output	Sinksheds Raster

Table C.1. Tool Parameters for Creation of Sinksheds

Stream Features Creation Parameters

Tool	Parameter	Setting
Stream Order	Input	Accumulation Raster
	Input	Flow Direction Raster
	Output	Stream Order Raster
	Method of Stream Ordering	Strahler
Stream to Feature	Input	Stream Order Raster
	Input	Flow Direction Raster
	Output	Stream Order Vectors

Table C.2. Tool Parameters for Creation of Surface Stream Features

Sink Low Points Creation Parameters

Tool	Parameter	Setting
Int	Input	30 ft DEM (floating point data type)
	Output	30 ft DEM (Integer data type)
Raster to Point	Input	30 ft DEM (Integer)
	Field	Elevation
	Output	Elevation point features
Spatial Join	Target Features	Sinkshed polygons
	Join Features	Elevation Points
	Output Feature Class	Sinkshed polygons w/ many elevation values
	Join Operation	Join one to many
	Join Options	Keep All Target Features
	Summarize	Minimum (minimum elevation for each sinkshed ID)
Spatial Join	Target Features	Elevation Points
	Join Features	Sinksheds with elevation minimum
	Output Feature class	Elevation points with elevation and minimum elevation w/in sinkshed
	Join Operation	One to One
	Join Options	Keep All Target Features
Selection by Attributes	Input	Elevation points with low elevation attribute
	Formula	Select where elevation = low elevation
Export Selection	Selection	Points where low elevation equals actual elevation
	Output	Low point(s) by sinkshed shapefile

Table C.3. Tool and Form Parameters for Creating Sinkshed Low Points

Creation of Network Dataset in ArcCatalog

Tool	Parameter	Setting
New Network Dataset	Features Participating	Stream Order Features
	Modify connectivity with elevation	No
	Model turns	Yes
	Attributes for Network	Length (Cost – Feet – Double)
	Evaluators of Attribute: From-To	Field – Distance in feet
	Evaluators of Attribute: To-From	Constant - 10000000
	Driving Directions	No

Table C.4. Tool Parameters for Creating a Network Dataset for Surface Water Runoff – ArcCatalog

Network Analysis Parameters – ArcMap

Tool	Parameter	Setting
Network Analyst: New Closest Facility	Facilities	Trial 1: drywells Trial 2: other karst features Trial 3: low points
	Incidents	RCRA sites
	Accumulation	Length (Feet)
	Network location	Closest w/in 50 feet of stream features
	Settings: Facilities to find	1
	Settings: Travel From	Incident to Facility
	Settings: Allow U-Turns	Nowhere
	Output	Routes from Incidents to Facilities

Table C.5. Tool Parameters for Network Analysis in ArcMap – Surface Water Runoff Pathways

Spatial Interpolation and Potentiometric Surface Creation

Tool	Parameter	Setting
Geostatistical Analyst – Geostatistical Wizard	Method	Local Polynomial Interpolation
	Input data	Point shapefile of wells, springs, and stream points with elevations
	Attribute	Elevation Field
	Power	2
	Neighborhood	20% global affects 80% local affects
Buffer	Input	Streams line shapefile
	Buffer size	120 feet
	Output	Polygon of the area 120 feet around stream centerline
Polygon to Raster	Input	Streams polygon shapefile
	Output	Streams polygon raster
Extract By Mask	Input	DEM of the Study Area (Integer data type), Buffered streams polygon raster
	Output	Elevation raster of just the area of the buffered streams
Map Algebra – Single Output Map Algebra	Map Algebra Expression	Merge([Stream Elevation Raster], [Potentiometric Surface Raster])
	Output Raster	Single Merged Raster

Table C.6. Tool Parameters for Spatial Interpolation of Potentiometric Surface

Hydrological Analysis for Subsurface Stormwater Pathways

Tool	Parameter	Setting
Fill	Input	Kriging ground water surface
	Output	Filled ground water surface
	z-limit	none
Flow Direction	Input	Filled ground water surface
	Output	Flow direction raster (shows the direction from each cell to is steepest downslope neighbor)
	Additional output	Flow drop raster (change in elevation expressed in percentage)
Watershed	Input	Flow direction raster
	Input	Point data of springs within 500m of NHD surface flow
	Input Field	ID
	Output	Watershed raster for springs along NHD water features within the area of interest

Table C.7. Tool Parameters for Creating Subsurface Pathways